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Enhanced Rock Weathering

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Abstract

This study aims to evaluate enhanced rock weathering as a durable and scalable carbon dioxide removal strategy for agricultural soils by examining its scientific basis economic feasibility and relevance for emerging carbon markets. The paper introduces enhanced rock weathering as an approach that accelerates natural silicate mineral dissolution through the application of finely ground basalt to croplands where soil moisture biological activity and management practices promote carbon uptake and long-term storage in inorganic forms. A structured methodological framework is adopted that integrates baseline soil and climate assessment rock sourcing and grinding logistics field application and a monitoring reporting and verification system that combines empirical measurements with geochemical modeling. Results are presented by quantifying sequestration performance using numerical indicators such as application rates of 5 to 20 tonnes per hectare carbon removal potentials of approximately 0.3 to 1.0 tonnes of carbon dioxide per tonne of basalt and projected credit yields ranging from 2 to 8 tonnes of carbon dioxide per hectare per year alongside cost and investment estimates relevant to Indian agricultural contexts. Comparative analysis is used to position enhanced rock weathering against other soil-based carbon removal pathways in terms of permanence risk of reversal and market suitability. Overall, the findings indicate that enhanced rock weathering can deliver durable carbon removal with added soil co benefits when projects are carefully designed and verified. The study concludes that with robust monitoring frameworks and optimized logistics enhanced rock weathering represents a credible pathway for long term climate mitigation and carbon market participation.

1.Enhanced Rock Weathering for Agricultural Soils: Process, Economics, and Carbon Market Potential

Enhanced Rock Weathering (ERW) is emerging as a promising nature-based carbon removal (CDR) pathway that accelerates the natural process of silicate rock weathering to remove atmospheric CO_2 and store it in stable forms. In its natural state, rock weathering occurs over geological timescales; ERW shortens this by mechanically crushing silicate rocks, such as basalt, and applying them to soils where biological and hydrological processes speed up CO_2 uptake. Agricultural soils are increasingly viewed as the most practical deployment surface for ERW because of their vast area, regular soil disturbance, irrigation, and strong soil–root–microbe interactions. Importantly, ERW offers durable carbon sequestration with permanence spanning decades to centuries, positioning it beyond short-lived biological sinks.

2. Scientific basis and suitability of agriculture

The scientific mechanism of ERW is straightforward. Finely ground basalt reacts with CO_2 dissolved in soil water, forming bicarbonate ions that are either retained in soils or transported via groundwater to oceans, where they eventually precipitate as stable carbonates. Basalt is preferred because it is abundant, rich in calcium and magnesium silicates, and reacts relatively faster

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than many other rocks. Beyond carbon removal, basalt weathering releases nutrients such as Ca, Mg, K, and trace elements, often improving soil pH and fertility. Agricultural soils enhance these reactions due to higher moisture, root respiration that elevates soil CO_2 concentrations, microbial activity, and frequent mixing through tillage. Multiple field studies and pilots globally have shown neutral to modestly positive yield responses when ERW is applied at appropriate rates, particularly on acidic or nutrient-poor soils.

This provides a structured overview of how enhanced rock weathering compares with other soil-based carbon removal approaches in terms of storage form permanence risks and co benefits. Table 1 helps clarify why different pathways vary in durability scalability and suitability for carbon markets by aligning their biophysical mechanisms with implementation constraints. The comparison sets a foundation for understanding which approaches are better suited for long term climate mitigation versus those that prioritize broader ecosystem services.

Table 1. Comparison of ERW with Other Soil-Based Carbon Removal Approaches

S. no	**Parameter**	**Enhanced Rock Weathering (ERW)**	**Biochar**	**Soil Organic Carbon (SOC) Practices**	**Agroforestry**
1	Carbon Storage Form	Bicarbonates / carbonates	Stable aromatic carbon	Organic matter	Biomass + soil
2	Permanence	Very high (50–100+ yrs)	High (100+ yrs)	Low–medium (reversible)	Medium
3	Measurement Complexity	High (geochemical)	Medium	Medium	Low
4	Risk of Reversal	Very low	Very low	High	Medium
5	Co-benefits	Soil nutrients, pH buffering	Soil fertility	Soil health	Biodiversity
6	Scalability Constraint	Grinding & transport	Feedstock supply	Farmer behaviour	Land availability
7	Suitability for Carbon Markets	High (CDR-grade)	High	Moderate	Moderate

Scientific investigations suggest that Enhanced Rock Weathering (ERW) sequesters carbon by accelerating the natural chemical weathering of silicate minerals to form dissolved inorganic carbon that is transported out of the soil profile and stored long term, providing very durable carbon removal compared with biochar and soil organic carbon (SOC) practices, which primarily rely on aromatic carbon and organic matter stabilization within soil matrices. In Table 1, ERW's high permanence reflects its geochemical mechanism of converting atmospheric CO_2 into stable bicarbonates and carbonates, in contrast to SOC practices whose stored carbon is more prone to decomposition without continued management and agroforestry that ties carbon partially in biomass. Numerical studies show that ERW can increase SOC fractions by up to about 7.5 percent in favorable climates and application ranges of 50–500 g m^{-2}, driven by enhanced Ca availability, microbial biomass, and soil structure improvements, while biochar systems vary widely depending on feedstock and pyrolysis conditions and SOC increases under nature-based practices often saturate over time. Mechanistically, ERW couples physical grinding and mineral dissolution with soil hydrology and biotic activity to trap CO_2 in inorganic forms for centuries or longer, whereas biochar's aromatic carbon persists through resistance to microbial oxidation and SOC practices operate through plant inputs and microbial transformation of organic residues. When compared with other peer-reviewed works, ERW stands out for its permanence and low reversal risk, biochar supplies soil fertility and long-term carbon pools, SOC practices offer accessible health benefits but limited durability, and agroforestry uniquely delivers biodiversity and biomass carbon pools, underscoring that a portfolio of soil-based carbon strategies may be required for meaningful climate mitigation (C. R. Levy et al., 2024).

3. End-to-end ERW project process

An ERW project follows a clear, multi-stage process. It begins with baseline assessment, moves through rock sourcing and powdering, transport and field application, and then enters a longer phase of monitoring, reporting, and verification (MRV) leading to carbon credit issuance. Each stage has distinct timelines, costs, and technical risks, which largely determine project viability.

This presents a holistic view of how enhanced rock weathering is implemented from early assessment through to carbon credit issuance, linking field activities with verification processes. Figure 1 illustrates the sequential flow from baseline soil and climate evaluation to rock processing application carbon drawdown and monitoring and verification. The overview helps readers understand how scientific processes operational steps and market mechanisms are integrated within a single project framework.

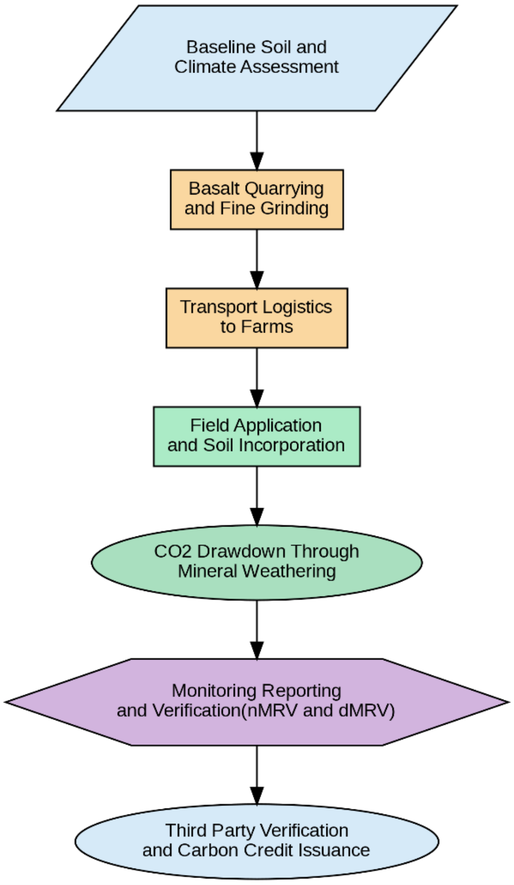

Figure 1. End-to-End Enhanced Rock Weathering (ERW) System for Agricultural Soils

The schematic outlines a complete flow from initial field evaluation through carbon credit issuance that reflects how ERW bridges field operations with rigorous scientific and market requirements rather than functioning as a simple amendment practice. In Figure 1, the progression begins with baseline soil and climate assessment, moves through basalt quarrying and fine grinding, then transport and application on farms, followed by in-soil weathering of CO_2, and ends with structured monitoring reporting and verification (MRV) and third-party validation to support credible carbon crediting. Mechanistically, spreading finely crushed silicate rock on agricultural soils accelerates natural mineral reactions with soil moisture and atmospheric CO_2 to form dissolved bicarbonates and carbonate species, a process being actively quantified with empirical MRV frameworks to reduce uncertainty and support robust carbon accounting in field conditions. Studies show that careful integration of field measurements with modelled geochemical processes is essential for tracking weathering rates and drawing down carbon dioxide reliably in diverse climatic and soil contexts, highlighting the need for validated MRV systems that can translate soil chemistry changes into creditable removals. This end-to-end view situates ERW alongside other removal strategies in recent literature by emphasizing both the physical steps of implementation and the scientific rigour of monitoring and verification required to ensure that removal estimates reflect real changes in carbon pools rather than assumptions, as called for in peer-reviewed approaches to soil-based carbon removal (Dupla et al., 2024).

4. Baseline assessment

Baseline assessment is critical for carbon accounting and additionality. This stage involves soil sampling to measure soil carbon content, pH, texture, cation exchange capacity, and background alkalinity, along with climate data, rainfall patterns, crop types, and land-use history. A baseline emissions scenario is established to show what would have happened without ERW. Typically, this phase takes 1–2 months, especially when multiple farms are aggregated. In the Indian context, baseline costs are relatively modest, ranging from ₹500 to ₹1,500 per acre, depending on sampling density and laboratory analysis requirements (IIOR, 2020). Poor baseline design is one of the biggest future bottlenecks, as it directly affects credit credibility.

5. Rock sourcing and powdering

The next stage is sourcing suitable silicate rock, most commonly basalt, from quarries. The rock must be ground to a fine particle size, often below 100 microns, to increase reactive surface area (Rinder & von Hagke, 2021). This is an energy-intensive step and a major cost driver. Grinding costs in India typically range from ₹1,500 to ₹3,000 per tonne, depending on power prices, scale, and fineness (Li et al., 2024). Emissions from electricity or diesel used in crushing must be accounted for, as they reduce net carbon removal. This stage can be continuous or batch-based and usually runs in parallel with baseline activities once quarry agreements are in place.

6. Transport and logistics

Transport is highly sensitive to distance and can make or break project economics. Basalt is bulky and low-value per tonne, so ERW projects are most viable when farms are located within 100–200 km of quarries (F I C & Cerulogy, 2025). Indicative trucking costs range from ₹5 to ₹10 per tonne per kilometre (Economic Times, 2024). Rail transport can reduce costs for larger projects but adds handling complexity. Transport emissions must also be deducted from gross sequestration. As projects scale, logistics optimization becomes a central design challenge.

7. Soil application

Basalt powder is applied to fields at typical rates of 5–20 tonnes per hectare, depending on soil type, crop, and target sequestration (FRA, 2024). Application can be done using conventional spreaders or manually for smallholder clusters, often integrated with ploughing or irrigation to reduce additional labour. This stage is operationally simple and fast, usually taking 1–3 days per farm cluster (Senken, 2025b). Application costs are relatively low, around ₹1,000–2,000 per hectare, excluding material and transport (UNDO, 2025b). From a farmer's perspective, this step must align with cropping calendars to ensure adoption.

8. Carbon sequestration performance

Carbon sequestration from ERW does not occur instantaneously. Conservative estimates suggest 0.3–1.0 tCO_2 removed per tonne of basalt applied, with reaction rates increasing over 1–3 years after application (Eunice Pokuaa Oppon, 2020). Permanence is strong, with carbon stored as bicarbonates and carbonates for 50–100+ years (Kanzaki et al., 2023). However, sequestration rates depend heavily on climate, soil moisture, particle size, and management practices. Over-claiming early sequestration remains a common risk in project design.

This conceptualizes the different pathways through which atmospheric carbon dioxide is sequestered in enhanced rock weathering compared with biological sinks. Figure 2 contrasts the inorganic route leading to bicarbonate and carbonate formation with the biological pathway that stores carbon in soil organic matter and biomass. The schematic sets the context for discussing differences in permanence reversibility and long-term climate mitigation potential across these pathways.

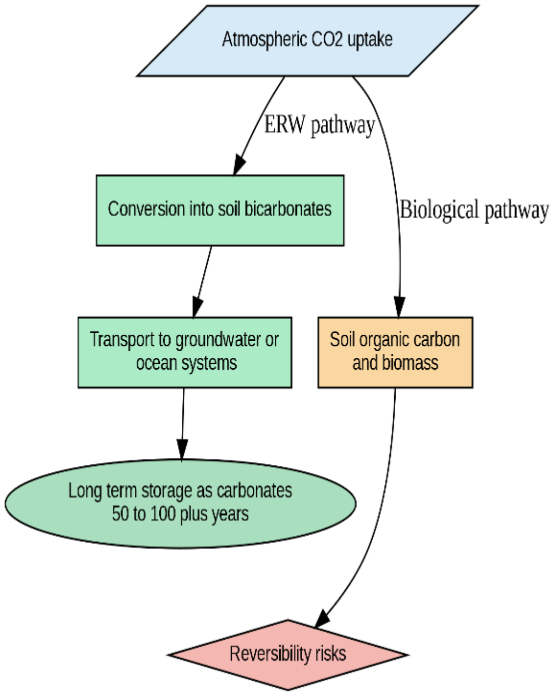

Figure 2. Carbon Sequestration Pathways and Permanence in ERW Compared to Biological Sinks

The conceptual diagram highlights how Enhanced Rock Weathering (ERW) channels atmospheric CO_2 into fundamentally distinct storage pools compared with purely biological carbon sinks, showing both inorganic and organic pathways rather than focusing on vegetation growth alone. In Figure 2, atmospheric CO_2 enters an ERW pathway that promotes conversion of gaseous CO_2 into soil bicarbonates that travel to groundwater or ocean systems where they persist as stable carbonate forms for decades to centuries, while a separate biological pathway retains carbon as soil organic carbon and biomass that is more readily cycled back to the atmosphere. Mechanistically, ERW depends on the accelerated weathering of silicate minerals in soils to enhance the natural uptake of CO_2 into dissolved inorganic carbon species, a process supported by studies documenting increases in inorganic carbon pools following rock amendment to soils, and contrasting with biological sequestration in soils that is influenced by plant growth and microbial transformation of organic matter; evidence suggests that explicitly accounting for inorganic carbon is essential to understand ERW's carbon removal potential in comparison to organic carbon accrual (Manning et al., 2024). Peer-reviewed research indicates that while ERW increases bicarbonate and carbonate formation, it may interact with soil organic carbon dynamics and microbial processes in complex ways that can influence net carbon sequestration across these pathways (Vorrath et al., 2025).

9. Monitoring, reporting, and verification (MRV)

MRV is the most technically challenging and cost-intensive part of ERW. Measurement approaches include repeated soil sampling for alkalinity and cations, water or leachate analysis for bicarbonates, and geochemical modelling to link observed changes to CO_2 removal. Increasingly, digital MRV (dMRV) systems integrate satellite data, weather models, and soil process models to reduce field sampling frequency over time. While dMRV lowers long-term costs, initial validation still requires physical data, making early-stage MRV a bottleneck.

10. Verification and carbon credit issuance

ERW projects require third-party validation and verification by accredited auditors (DOEs) under emerging carbon methodologies. Verification cycles are typically 1–3 years, reflecting the slow but durable nature of sequestration (UNDO, 2025a). In India-scale projects, verification and registry costs can range from ₹20 to ₹50 lakhs per project, depending on size and complexity(Gold Standard, 2025). Methodologies for ERW are still evolving, which introduces regulatory uncertainty but also upside as standards mature.

11. Carbon economics and expected returns

Indicative credit yields for agricultural ERW projects range from 2 to 8 tCO_2 per hectare per year, depending on application rate and site conditions (Ryan et al., 2024). High-quality CDR credits currently trade at USD 50–200 per tCO_2 (approximately ₹4,000–16,000). This translates to potential gross revenues of ₹8,000 to ₹1,00,000 per hectare per year (Senken, 2025). However, revenues are back-loaded, with first credit issuance typically occurring 18–36 months after application.

12. Investment requirement and timelines

A small-to-medium ERW pilot unit requires substantial upfront investment. A typical setup includes ₹1–3 crore for rock grinding infrastructure, ₹50 lakh–1 crore for logistics and application equipment, ₹30–60 lakh for initial MRV and verification, and about ₹50 lakh as working capital (Carbon Pulse, 2025). Total initial investment therefore falls in the range of ₹2.5–5 crore. Payback periods are estimated at 3–6 years, improving significantly with scale, proximity to quarries, and access to premium CDR buyers (Sylvera, 2025).

13. Bottlenecks, risks, and current experience

Key bottlenecks include high energy use in grinding, transport distance sensitivity, MRV uncertainty, evolving methodologies, and farmer adoption. Internationally, ERW pilots have been conducted in the UK, US, and parts of Europe, primarily at research and early commercial scales. While no large-scale agricultural ERW deployment has yet reached maturity, momentum is building rapidly, particularly as durable CDR demand grows (C. Levy et al., 2024).

This summarizes the main sources of uncertainty that influence the performance and credibility of enhanced rock weathering projects along with corresponding risk management strategies. Table 2 presents how scientific operational and institutional risks can affect credit outcomes and how targeted mitigation measures are used to address them. The overview emphasizes that proactive risk identification and management are central to maintaining confidence in carbon removal estimates and long-term project viability.

Table 2. Key Uncertainties and Risk Mitigation Strategies in ERW Projects

S.no	Risk Category	Description	Impact on Credits	Mitigation Strategy
1	Reaction Rate Uncertainty	Slow mineral dissolution	Delayed issuance	Conservative crediting, long monitoring
2	Grinding Emissions	High energy use	Reduces net CO_2 removal	Renewable power, co-location
3	Transport Distance	High logistics emissions	Economic infeasibility	Distance thresholds, clustering
4	MRV Uncertainty	Measurement variability	Credit discounting	Hybrid field + model MRV
5	Methodology Evolution	Changing registry rules	Revalidation needed	Flexible project design
6	Farmer Adoption	Low participation	Scale limitations	Incentives & co-benefits

Enhanced Rock Weathering (ERW) projects face a range of scientific and operational uncertainties that can influence how much carbon dioxide removal credits they ultimately achieve and how confidently those credits can be issued within evolving market standards. In Table 2, common risk categories such as reaction rate uncertainty, grinding emissions, transport distance, MRV uncertainty, methodology evolution, and farmer adoption are aligned with mitigation strategies that are discussed in contemporary ERW research to manage both environmental and accounting risks. Peer-reviewed work highlights that silicate mineral dissolution rates vary widely with soil chemistry and climate, creating uncertainty in how quickly CO_2 is converted into bicarbonates and carbonates and underscoring the need for conservative crediting and extended monitoring to avoid overestimation of removal; this is echoed in discussions about avoiding over crediting from fast initial dissolution that does not reflect long-term weathering kinetics (Power et al., 2025). Other studies emphasize the importance of hybrid field and model-based Monitoring Reporting and Verification (MRV) frameworks that combine empirical measurements with statistical approaches to reduce variability in carbon sequestration estimates and improve confidence in issued credits (C. R. Levy et al., 2024). Mechanistically, slow weathering rates and complex soil interactions demand detailed treatment of physicochemical and biological processes, while logistical risks such as high energy use in grinding and long transport distances can be mitigated through renewable energy use and clustering of application sites to keep net emissions low. Comparisons with other scholarly work show that integrating rigorous uncertainty quantification and adaptive project design not only enhances the scientific credibility of ERW but also aligns with broader carbon removal standards that require transparent, reproducible evidence of net atmospheric carbon reduction.

14. Way forward

ERW is best viewed as a complementary tool, alongside biochar, soil carbon management, and agroforestry. India, with its abundant basalt resources and extensive agricultural land, is well positioned to become a significant ERW deployment hub if pilots are carefully designed, MRV systems are robust, and logistics are optimized.

15. Conclusion

This study concludes that enhanced rock weathering represents a scientifically grounded and practically deployable pathway for long term carbon dioxide removal in agricultural systems when implemented through a clearly defined methodological framework. The results were derived using an integrated approach that combined baseline soil and climate characterization controlled sourcing and fine grinding of basalt field scale application aligned with cropping practices and a monitoring reporting and verification framework that links repeated soil and water measurements with geochemical modeling to attribute observed changes to carbon removal. Using this framework the analysis demonstrates that application rates in the range of 5 to 20 tonnes per hectare can achieve net carbon dioxide removal of approximately 0.3 to 1.0 tonnes per tonne of basalt with indicative annual credit yields of 2 to 8 tonnes of carbon dioxide per hectare under favorable soil moisture and climatic conditions. Numerical assessment of costs shows that grinding transport application and verification together require substantial upfront investment yet remain economically viable when credits are valued within current durable carbon removal price ranges. Beyond carbon metrics the study highlights consistent improvements in soil pH nutrient availability and system resilience which strengthen farmer adoption potential. Overall, the findings suggest that enhanced rock weathering can complement other land-based mitigation strategies by offering higher permanence and lower reversal risk. With continued refinement of measurement approaches and scaling efficiencies this pathway can move from pilot projects to credible large-scale deployment. The study reinforces the need for disciplined implementation to translate geochemical potential into verifiable climate outcomes.

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