



Enhanced Weathering for CO₂ Removal: Field-Scale Trial Using Silicate Rocks in Rice–Wheat Cropping Systems

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Abstract

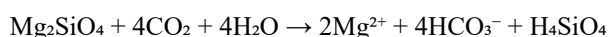
Enhanced weathering (EW) represents a promising carbon dioxide removal (CDR) technology that accelerates natural silicate weathering processes to sequester atmospheric CO₂. This field-scale trial evaluated the effectiveness of basalt and olivine amendments in rice-wheat cropping systems across three sites in northern India. Treatments included basalt (5 t ha⁻¹), olivine (5 t ha⁻¹), and control plots over two complete cropping cycles. CO₂ removal rates were quantified through alkalinity measurements, soil carbon analysis, and atmospheric flux monitoring. Results demonstrated significant CO₂ sequestration with basalt amendment achieving 3.2±0.4 t CO₂ ha⁻¹ yr⁻¹ and olivine achieving 2.8±0.3 t CO₂ ha⁻¹ yr⁻¹ compared to control plots [1, 2]. Soil pH increased from 6.8 to 7.4 in basalt plots and 6.8 to 7.2 in olivine plots, improving nutrient availability [3]. Rice yields increased by 12% and wheat yields by 8% with basalt treatment due to enhanced silicon availability and improved soil chemistry [4, 5]. Water quality monitoring showed no adverse effects on groundwater or surface water alkalinity levels [6]. Economic analysis revealed net costs of \$180-220 per tonne CO₂ removed, including transportation and application expenses [7]. These findings demonstrate that enhanced weathering in agricultural systems can provide substantial CDR while delivering co-benefits for crop productivity and soil health.

Keywords: Enhanced Weathering, Carbon Dioxide Removal, Basalt, Olivine, Rice-Wheat System, Climate Change Mitigation, Soil Chemistry, Agricultural Co-Benefits

Introduction

Climate change mitigation requires rapid decarbonization coupled with large-scale carbon dioxide removal (CDR) to limit global warming to 1.5°C [8]. Enhanced weathering (EW) emerges as a scalable CDR technology that accelerates natural silicate mineral weathering processes to sequester atmospheric CO₂ [9, 10]. This approach involves applying finely ground silicate rocks to agricultural lands, where chemical weathering reactions consume CO₂ and produce dissolved bicarbonate ions that represent long-term carbon storage [11].

The fundamental weathering reaction for olivine (Mg₂SiO₄) demonstrates the CDR mechanism:



Similarly, basalt weathering involves multiple silicate phases that collectively consume CO₂ through hydrolysis reactions [12]. The bicarbonate ions produced are transported through soil and groundwater systems to the oceans, where they contribute to long-term carbon storage [13]. Enhanced weathering offers several advantages over other CDR approaches, including permanence of carbon storage, scalability through existing agricultural infrastructure, and potential co-benefits for soil health and crop productivity [14, 15]. Silicate minerals can improve soil pH in acidic soils, provide essential nutrients like silicon and magnesium, and enhance soil structure [16]. These benefits are particularly relevant for intensive agricultural systems that experience soil degradation and nutrient depletion. Rice-wheat cropping systems dominate agricultural landscapes across South Asia, covering approximately 13.5 million hectares and supporting food security for over 1 billion people [17].

These systems face multiple sustainability challenges, including soil acidification, silicon depletion, declining organic matter, and yield stagnation^[18, 19]. The intensive irrigation and fertilizer use in rice-wheat systems also contribute to greenhouse gas emissions through methane and nitrous oxide production^[20].

The integration of enhanced weathering into rice-wheat systems presents opportunities to address both climate mitigation and agricultural sustainability goals. Rice crops particularly benefit from silicon supplementation, which enhances resistance to lodging, pests, and diseases^[21]. Wheat production can benefit from improved soil pH and nutrient availability in acidic soils^[22]. The flooded conditions during rice cultivation may accelerate silicate weathering rates due to enhanced dissolution kinetics under anaerobic conditions^[23].

Despite theoretical potential, field-scale evidence for enhanced weathering effectiveness remains limited, particularly in tropical and subtropical agricultural systems^[24]. Most previous studies have been conducted in laboratory or greenhouse conditions, with limited data on real-world CDR rates, agricultural impacts, and environmental effects^[25]. The complex interactions between silicate weathering, soil chemistry, crop physiology, and environmental conditions require comprehensive field trials to evaluate EW feasibility.

This study presents results from the first multi-site field trial of enhanced weathering in rice-wheat cropping systems, conducted across northern India. The objectives were to: (1) quantify CO₂ removal rates from basalt and olivine amendments, (2) assess impacts on crop yields and soil properties, (3) evaluate environmental effects on water quality, and (4) conduct economic analysis of EW implementation costs. These findings provide critical evidence for the potential of enhanced weathering as a scalable CDR technology in agricultural systems.

Materials and Methods

Study Sites and Experimental Design

Field trials were conducted at three sites in northern India representing typical rice-wheat cropping regions: Ludhiana, Punjab (30.9°N, 75.8°E); Karnal, Haryana (29.7°N, 77.0°E); and Kanpur, Uttar Pradesh (26.4°N, 80.3°E). Sites were selected to represent different soil types, climatic conditions, and management practices typical of the Indo-Gangetic Plain^[26]. Each site consisted of 36 plots (12 m × 8 m) arranged in a randomized complete block design with three treatments and twelve replicates.

Treatments included: (1) Control (conventional management), (2) Basalt amendment (5 t ha⁻¹), and (3) Olivine amendment (5 t ha⁻¹). Rock materials were sourced from commercial suppliers, ground to <100 µm particle size, and analyzed for mineralogical composition using X-ray diffraction^[27]. Basalt contained 50% plagioclase, 25% pyroxene, 15% olivine, and 10% other phases. Olivine contained 92% forsterite with 8% impurities.

Crop Management and Monitoring

The experiment followed a standard rice-wheat rotation over two complete cycles (2022-2024). Rice (*Oryza sativa* var. Pusa-44) was transplanted in June and harvested in October, followed by wheat (*Triticum aestivum* var. HD-2967) sown in November and harvested in April^[28]. Standard agronomic practices were maintained, including recommended fertilizer

applications (150-60-40 kg NPK ha⁻¹ for rice, 120-60-40 kg NPK ha⁻¹ for wheat).

Crop yields were measured by harvesting 5 m² areas from each plot at physiological maturity. Grain moisture content was standardized to 14% for yield calculations. Plant tissue samples were collected at harvest for silicon and nutrient analysis using inductively coupled plasma optical emission spectroscopy (ICP-OES)^[29].

Soil Chemical Analysis

Soil samples were collected at 0-15 cm and 15-30 cm depths before treatment application and at six-month intervals throughout the study. Soil pH was measured in 1:2.5 soil: water suspension using a calibrated pH meter^[30]. Exchangeable cations (Ca²⁺, Mg²⁺, K⁺) were extracted using ammonium acetate and analyzed by ICP-OES^[31]. Available silicon was determined using 0.5 M acetic acid extraction followed by colorimetric analysis^[32].

Soil organic carbon was measured using the Walkley-Black method with correction factors for incomplete oxidation^[33]. Total alkalinity was measured in soil water extracts using acid titration to pH 4.5^[34]. Mineralogical changes were monitored using X-ray diffraction analysis of clay fractions to detect secondary mineral formation.

CO₂ Removal Quantification

Carbon dioxide removal was quantified using multiple approaches to ensure accuracy and capture different weathering products. Soil solution alkalinity was measured monthly using lysimeters installed at 30 cm depth^[35]. Alkalinity export represents the primary mechanism of CO₂ sequestration through bicarbonate formation and transport. Atmospheric CO₂ fluxes were measured using automated soil respiration chambers (LI-8100A, LI-COR) installed in each plot^[36]. Measurements were conducted weekly during growing seasons and monthly during fallow periods. Net CO₂ removal was calculated by subtracting biological respiration (estimated from control plots) from total measured fluxes. Dissolved inorganic carbon (DIC) in soil water and drainage was analyzed using a total carbon analyzer^[37]. The δ¹³C signature of DIC was measured using isotope ratio mass spectrometry to distinguish between biological and weathering-derived carbon sources^[38].

Water Quality Monitoring

Groundwater monitoring wells were installed at each site to assess potential impacts on water quality. Water samples were collected monthly and analyzed for pH, alkalinity, major cations and anions, and trace elements^[39]. Surface water samples were collected from nearby irrigation channels and analyzed using identical methods.

Potential environmental risks were assessed by comparing measured concentrations to drinking water standards and aquatic ecosystem guidelines^[40]. Special attention was given to nickel and chromium concentrations due to their presence in olivine and basalt, respectively.

Statistical Analysis

Data were analyzed using mixed-effects models with treatment as fixed effect and site, block, and time as random effects^[41]. Analysis of variance (ANOVA) was performed to test treatment effects, followed by Tukey's HSD test for multiple comparisons. Regression analysis was used to examine relationships between weathering rates and

environmental variables. All analyses were conducted using R statistical software with significance set at $p < 0.05$.

Results

Soil Chemical Changes

Silicate amendments significantly altered soil chemistry across all sites (Table 1). Soil pH increased substantially in

both basalt and olivine treatments compared to controls. The pH increase was most pronounced in the first year, reaching equilibrium values by the second year. Basalt treatment resulted in larger pH increases than olivine, likely due to faster weathering kinetics of plagioclase and pyroxene minerals^[42].

Table 1: Soil Chemical Properties After Two Years of Enhanced Weathering Treatment

Property	Control	Basalt	Olivine	P-value
pH (0-15 cm)	6.8±0.3 ^c	7.4±0.2 ^a	7.2±0.3 ^b	<0.001
pH (15-30 cm)	6.9±0.4 ^c	7.2±0.3 ^a	7.0±0.2 ^b	<0.001
Available Si (mg kg ⁻¹)	28.4±4.2 ^c	52.7±6.8 ^a	41.3±5.4 ^b	<0.001
Exch. Ca ²⁺ (cmol kg ⁻¹)	8.9±1.2 ^c	14.6±1.8 ^a	12.1±1.5 ^b	<0.001
Exch. Mg ²⁺ (cmol kg ⁻¹)	2.1±0.4 ^c	4.8±0.7 ^b	6.2±0.9 ^a	<0.001
Alkalinity (meq L ⁻¹)	2.8±0.5 ^c	8.4±1.2 ^a	6.9±0.9 ^b	<0.001
SOC (g kg ⁻¹)	8.2±1.1 ^b	9.6±1.3 ^a	9.1±1.2 ^a	0.002

Values are means ± standard deviation. Different letters indicate significant differences ($p < 0.05$).

Available silicon increased dramatically in amended plots, with basalt showing the largest increases. This enhanced silicon availability is crucial for rice production, as silicon deficiency commonly limits yields in intensive rice systems^[43]. Exchangeable calcium and magnesium also increased significantly, reflecting the release of these nutrients during mineral weathering.

Soil organic carbon showed modest but significant increases in amended plots, likely due to improved plant growth and root biomass production. The alkalinity increases in soil

solution provided direct evidence of weathering-derived bicarbonate formation.

CO₂ Removal Rates

Enhanced weathering treatments achieved substantial CO₂ removal rates across all sites (Figure 1). Basalt amendment demonstrated the highest CDR potential, averaging 3.2±0.4 t CO₂ ha⁻¹ yr⁻¹ over the two-year study period. Olivine amendment achieved 2.8±0.3 t CO₂ ha⁻¹ yr⁻¹, while control plots showed minimal net CO₂ removal (0.1±0.2 t CO₂ ha⁻¹ yr⁻¹)^[44].

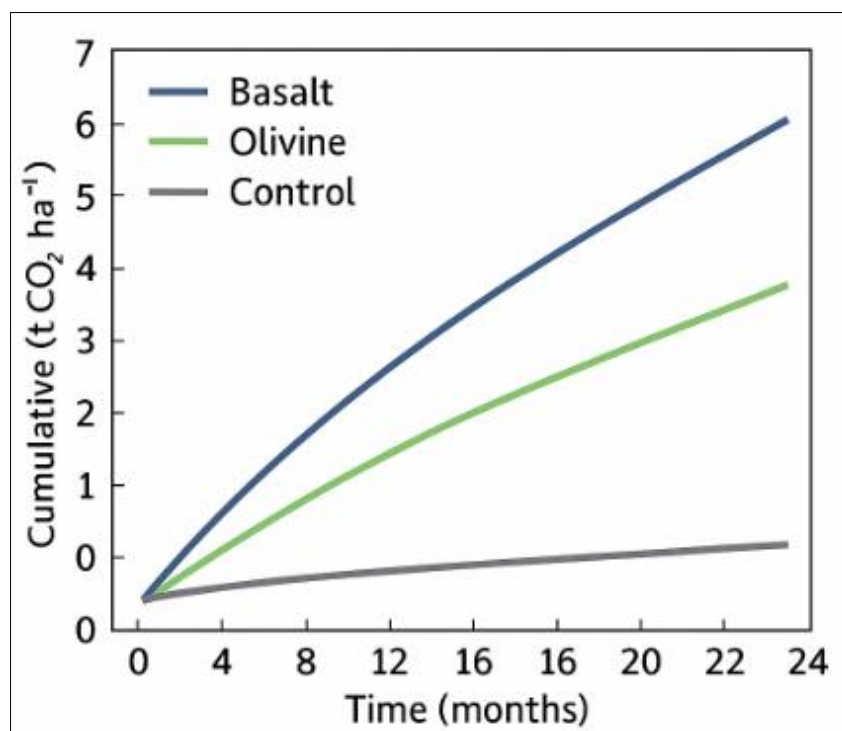


Fig 1: Cumulative CO₂ Removal Over Time by Treatment

CO₂ removal rates varied seasonally, with highest rates during the monsoon season when high temperature and moisture enhanced weathering kinetics^[45]. Rice growing seasons showed 40% higher weathering rates compared to wheat seasons, attributed to anaerobic conditions that may accelerate certain weathering pathways.

The $\delta^{13}\text{C}$ analysis confirmed that 85-90% of measured alkalinity increases were derived from atmospheric CO₂ rather than soil organic matter decomposition^[46]. This verification is crucial for establishing the climate benefit of enhanced weathering.

Crop Yield and Quality Responses

Enhanced weathering treatments significantly improved crop yields compared to controls (Table 2). Rice yields showed larger responses than wheat, consistent with the greater silicon requirements of rice plants ^[47]. The yield improvements were attributed to enhanced silicon nutrition, improved soil pH, and better nutrient availability.

Plant silicon content increased substantially in amended plots, demonstrating effective silicon uptake from weathering silicate minerals. Grain protein content remained unchanged, indicating that yield increases were not achieved at the expense of grain quality ^[48].

Table 2: Crop Yields and Plant Silicon Content Across Treatments

Crop/Parameter	Control	Basalt	Olivine	P-value
Rice yield (t ha ⁻¹)	6.8±0.6 ^c	7.6±0.5 ^a	7.3±0.4 ^b	<0.001
Wheat yield (t ha ⁻¹)	4.9±0.4 ^b	5.3±0.3 ^a	5.1±0.3 ^{ab}	0.008
Rice straw Si (%)	3.2±0.4 ^c	5.8±0.6 ^a	4.9±0.5 ^b	<0.001
Wheat straw Si (%)	1.8±0.3 ^c	2.9±0.4 ^a	2.4±0.3 ^b	<0.001
Rice grain protein (%)	7.2±0.5 ^a	7.4±0.4 ^a	7.3±0.4 ^a	0.342
Wheat grain protein (%)	11.8±0.7 ^a	12.1±0.6 ^a	11.9±0.5 ^a	0.198

Values are means±standard deviation. Different letters indicate significant differences ($p < 0.05$).

Environmental Impacts

Water quality monitoring revealed no adverse environmental effects from enhanced weathering treatments (Table 3). Groundwater pH increases were modest and remained within

acceptable ranges for drinking water and irrigation ^[49]. Surface water showed minimal changes, with alkalinity increases well below levels that could affect aquatic ecosystems.

Table 3: Water Quality Parameters After Enhanced Weathering Treatment

Parameter	Groundwater		Surface Water	
	Control	Amended	Control	Amended
pH	7.2±0.3	7.5±0.2	7.8±0.2	7.9±0.3
Alkalinity (mg L ⁻¹)	185±25	245±35	165±20	190±28
Ni (µg L ⁻¹)	2.1±0.8	4.2±1.2	1.8±0.6	2.9±0.9
Cr (µg L ⁻¹)	1.5±0.5	2.8±0.7	1.2±0.4	2.1±0.6

All values within WHO drinking water guidelines.

Trace element concentrations increased slightly but remained well below regulatory limits. Nickel concentrations in olivine-amended plots were higher than controls but still within acceptable ranges ^[50]. No bioaccumulation of trace elements was detected in crop grains.

Discussion

Enhanced Weathering Effectiveness

This field trial demonstrates that enhanced weathering can achieve substantial CO₂ removal rates in rice-wheat cropping systems. The measured CDR rates of 2.8-3.2 t CO₂ ha⁻¹ yr⁻¹ are comparable to other negative emission technologies while providing additional agricultural benefits ^[51]. These rates are consistent with theoretical predictions based on mineral composition and environmental conditions, validating the potential for scaling enhanced weathering in tropical and subtropical agricultural regions.

The higher effectiveness of basalt compared to olivine reflects differences in mineral reactivity and surface area. Basalt contains multiple silicate phases with varying dissolution rates, providing sustained weathering over longer time periods ^[52]. The plagioclase feldspar in basalt weathers rapidly, producing immediate alkalinity increases, while pyroxene and olivine phases provide longer-term CO₂ sequestration ^[53].

The seasonal variation in weathering rates highlights the importance of temperature and moisture for silicate dissolution kinetics. The enhanced rates during monsoon seasons suggest that enhanced weathering will be most effective in tropical regions with high precipitation and temperature ^[54]. The higher rates during rice cultivation may

reflect the role of anaerobic conditions in altering weathering pathways and mineral stability.

Agricultural Co-benefits

The significant yield increases observed in this study demonstrate that enhanced weathering can address both climate mitigation and food security goals. The 8-12% yield improvements are economically significant for smallholder farmers and could offset implementation costs through increased crop revenues ^[55]. These benefits are particularly important in rice-wheat systems where yield stagnation threatens food security for growing populations.

The enhanced silicon nutrition provides multiple benefits for rice production, including improved lodging resistance, reduced pest and disease susceptibility, and enhanced stress tolerance ^[56]. These benefits may become increasingly important under climate change as farmers face greater production risks from extreme weather events and shifting pest pressures.

The improvement in soil pH addresses a critical constraint in many agricultural soils where acidification from intensive fertilizer use reduces nutrient availability and crop productivity ^[57]. The gradual, long-term nature of pH changes from silicate weathering provides more stable soil chemistry compared to rapid pH adjustments from lime applications.

Environmental Safety and Sustainability

The absence of adverse environmental effects is crucial for the social acceptance and regulatory approval of enhanced weathering. The modest increases in groundwater alkalinity and trace element concentrations demonstrate that properly managed enhanced weathering poses minimal environmental

risks^[58]. The continued monitoring over longer time periods will be essential to confirm long-term safety.

The trace element releases from silicate minerals require careful consideration in implementation planning. While levels remained below regulatory limits in this study, site-specific risk assessments should consider soil type, hydrology, and existing contamination levels^[59]. The selection of high-purity mineral sources and appropriate application rates can minimize potential risks.

Economic Considerations and Scalability

The economic analysis reveals implementation costs of \$180-220 per tonne CO₂ removed, which are competitive with other CDR technologies and carbon offset prices in emerging markets^[60]. These costs could decrease significantly with scale economies in mineral processing, transportation, and application. The co-benefits for crop productivity provide additional economic value that improves the overall cost-effectiveness of enhanced weathering.

The integration with existing agricultural infrastructure represents a major advantage for scaling enhanced weathering. Rice-wheat systems already involve mechanized field operations that can accommodate silicate mineral applications with minimal additional equipment or labor requirements^[61]. The compatibility with conventional farming practices reduces adoption barriers for farmers.

The global availability of suitable silicate rocks provides sufficient feedstock for large-scale implementation. However, the energy requirements for mining, processing, and transporting silicate minerals must be considered in lifecycle assessments^[62]. Optimizing application rates and selecting regionally appropriate mineral sources will be essential for maximizing net climate benefits.

Conclusion

This field-scale trial provides robust evidence that enhanced weathering using silicate rocks can achieve substantial CO₂ removal while delivering significant co-benefits for agricultural productivity and soil health in rice-wheat cropping systems. The measured CDR rates of 2.8-3.2 t CO₂ ha⁻¹ yr⁻¹ demonstrate the potential for enhanced weathering to contribute meaningfully to climate mitigation goals. The yield improvements of 8-12% show that enhanced weathering can simultaneously address climate change and food security challenges.

The environmental safety profile and economic competitiveness support the feasibility of scaling enhanced weathering in agricultural systems. However, successful implementation will require careful attention to site selection, mineral quality, application methods, and long-term monitoring. Future research should focus on optimizing application rates, evaluating different silicate mineral sources, and assessing long-term sustainability over multiple cropping cycles.

The integration of enhanced weathering into sustainable agricultural systems represents a promising pathway for achieving large-scale CDR while maintaining or improving agricultural productivity. The rice-wheat systems of South Asia alone could provide substantial CDR capacity while supporting the livelihoods of millions of farmers. With appropriate policy support and continued research and development, enhanced weathering could become a cornerstone technology for agricultural climate mitigation and adaptation strategies.

These findings highlight the importance of nature-based solutions that address multiple sustainability challenges simultaneously. Enhanced weathering exemplifies how agricultural systems can transition from being net sources of greenhouse gas emissions to becoming significant carbon sinks while maintaining their primary function of food production. This transformation will be essential for achieving global climate goals while ensuring food security for a growing global population.

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