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CO_2 Sequestration and Soil Improvement in Enhanced Rock Weathering: A Review from an Experimental Perspective

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Abstract

Enhanced Rock Weathering (ERW) is an emerging Negative Emission Technology (NET) with significant potential for mitigating climate change and improving soil health through the accelerated chemical weathering of silicate minerals. This study adopts a critical research approach to review existing ERW experiments, focusing on the mechanisms of soil improvement and CO_2 sequestration, as well as the economic costs and environmental risks associated with its large-scale implementation. The results demonstrate that while ERW effectively enhances soil pH and provides essential nutrients for crops, its CO_2 sequestration capacity is highly dependent on variables such as soil type, rock type, application rate, and particle size. Furthermore, the economic feasibility of ERW is challenged by high costs related to mining, grinding, and transportation, and environmental risks posed by the release of heavy metals like Ni and Cr during the weathering process. Notably, significant discrepancies exist between laboratory experiments and field applications, highlighting the need for extensive in-situ monitoring and adjustment of ERW practices. This study underscores the importance of optimizing ERW strategies to maximize CO_2 sequestration while minimizing environmental impacts. Future research should focus on long-term field experiments, understanding secondary mineral formation, and refining the application techniques to enhance the overall efficiency and sustainability of ERW.

Keywords: Enhanced rock weathering; Experiments; Negative emissions technology; CO_2 storage; Soil improvement

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1. Introduction

The phenomenon of global climate change has become one of the most significant challenges currently facing the world. It has been widely acknowledged that the continued emission of CO_2 represents a major contributing factor to this phenomenon. In order to address this issue, governments and the scientific community are actively investigating a range of climate change mitigation and adaptation strategies (UNFCCC). Enhanced rock weathering (ERW), a type of negative emissions technology (NET), has garnered significant attention in recent years. ERW is designed to capture and store atmospheric CO_2 by accelerating the natural weathering process, and it can simultaneously improve soil quality and increase crop production(Beerling et al. 2020). In nature, rocks undergo chemical weathering in the presence of CO_2 to produce carbonates and silicates, thereby contributing to the Earth's carbon cycle. However, the natural rate of this process is relatively slow, rendering it challenging to effectively reduce atmospheric CO_2 concentrations within a limited timeframe(Hilton and West 2020). The objective of enhanced rock weathering is to accelerate the rate of rock weathering through human intervention, thereby achieving the goal of carbon sequestration in a more expeditious manner and simultaneously enhancing soil quality to ensure a symbiotic relationship between the two processes.

The advantages of enhanced rock weathering include a significant potential for carbon sequestration, a reduced reliance on other net water resources, and the capacity to release ions that promote crop growth during the weathering process (Smith et al. 2016; Swoboda, Döring, and Hamer 2022; Eufrasio et al. 2022). The potential for ERW technology to sequester CO_2 on a global scale has been estimated by various studies to range from hundreds of millions to billions of tons per year(Kantzas et al. 2022). Furthermore, ERW does not necessitate the use of sophisticated technical equipment and can be implemented in a variety of geographical settings with minimal preparatory work. Nevertheless, the extensive implementation of ERW continues to encounter significant obstacles, including the financial burden associated with mineral crushing and transportation, the variability in weathering rates across different geographical regions, and the potential environmental consequences. These challenges necessitate further investigation and practical experimentation to facilitate the advancement of this technology (Kelland et al. 2020; Beerling et al. 2020; te Pas, Hagens, and Comans 2023).

Previous reviews have concentrated on the mechanisms of enhanced rock weathering, for example, how ERW accelerates the mineralization of rock flour with CO_2 to produce stable carbonate minerals for long-term CO_2 storage (Swoboda, Döring, and Hamer 2022; Hartmann et al. 2013); how ERW affects amelioration of soils, for example, increasing soil pH to slow soil acidification and agricultural production(Haque et al. 2019; Lamb et al. 2016; Abdalqadir et al. 2024). Additionally, certain studies have evaluated the life cycle of ERW and analyzed the costs of ERW (Jerden et al. 2024; Lefebvre et al. 2019; Beerling et al. 2020).

This study employs a critical research approach to systematically review and analyze existing experiments on ERW from an experimental perspective. By thoroughly evaluating the rationale, design, results, and consistency of various experiments, the study aims to identify the gaps between theory and practice in ERW technology and to explore the challenges and limitations of its practical application. The research begins by elucidating the fundamental principles of ERW, establishing a theoretical foundation for the subsequent chapters. Following this, a critical analysis of experimental data on soil improvement and CO_2 sequestration in ERW is conducted to deeply examine its actual effectiveness and potential issues. Finally, the study reviews the costs, environmental risks involved in the implementation of ERW, and provides insights and recommendations for future research and technological development. Through this critical review of ERW experiments, the paper aspires to offer valuable insights for future research and technological applications, advancing the practical deployment of ERW technology in addressing global climate change and promoting sustainable agricultural development. The articles selected in this paper are mainly researches conducted in the past five years, some of which have not been studied in recent years, and previous articles are selected as references.

2. Mechanism

ERW is a natural carbon sequestration process driven by accelerated chemical weathering of silicate rocks. This process involves the dispersal of fractured calcium- and magnesium-rich silicate rocks to the surface or ocean, where they react with atmospheric CO_2 and moisture to form stable carbonates and other compounds(Hartmann et al. 2013). It is estimated that 90% of the rocks exposed at the surface are silicate rocks. However, not all silicates are suitable for ERW. In fact, sedimentary and metamorphic silicates make up 79.1% of the land surface and have a low calcium and magnesium content (White and Brantley 2003; Suchet, Probst, and Ludwig 2003). Basalt, a basaltic ejecta, is widely distributed on the surface and is also rich in calcium and magnesium ions. In contrast, peridotite exhibits a markedly elevated magnesium content, although it is considerably more costly to extract and is less widely distributed in comparison to basalt. A multitude of experiments have demonstrated the CO_2 absorption capacity of basalt and peridotite. However, the presence of elevated concentrations of the toxic metals Ni and Cr in these two rocks can result in their accumulation in the soil (te Pas, Hagens, and Comans 2023; Pogge Von Strandmann et al. 2022). Wollastonite, a mineral that is susceptible to rapid weathering, also exhibits considerable CDR potential (Haque et al. 2019; Kelland et al. 2020; Taylor et al. 2021). Enhanced weathering may be conceptualized as a process whereby a primary mineral, such as feldspar, is converted into a secondary product, namely clay minerals, through the neutralization of atmospheric carbonic acid.

Atmospheric CO_2 dissolves in water:

$$\mathrm{CO_2 + H_2O \leftrightarrow HCO3^- + H^+} \tag{1}$$

Dissolution of basalt:

$$\mathrm{(Fe, Ca, Mg)Al_2Si_2O + 8H^+ \leftrightarrow (Fe, Ca, Mg)^{2+} + 2Al^{3+} + 2SiO_2 + 4H_2O} \tag{2}$$

Dissolution of olivine:

$$\mathrm{4H^+ + (Fe, Mg)_2SiO_4 \leftrightarrow 2(Fe, Mg)^{2+} + H_4SiO_4} \tag{3}$$

Dissolution of wollastonite:

$$\mathrm{2H^+ + CaSiO_3 \leftrightarrow Ca^{2+} + H_2O + SiO_2} \tag{4}$$

The chemical weathering process of silicate rocks also has an impact on soil and water bodies. Cations such as calcium, magnesium, and sodium released during weathering help to neutralize soil acidity and increase soil pH, thus improving crop growing conditions (Beerling et al. 2018; Blanc-Betes et al. 2021). Silicate rock powder (SRP) is mainly used in highly weathered soils prevalent in the humid and semi-humid tropics, as temperature and water are important factors affecting rock dissolution, with a decrease in temperature reducing the rate of rock weathering by several orders of magnitude, whereas for rock dissolution, solution has always been important (Pogge Von Strandmann et al. 2022; Schopka, Derry, and Arcilla 2011). As rocks dissolve, total alkalinity in the soil increases. Total Alkalinity (TA) is the total concentration of alkaline substances in water that can neutralize acids. It mainly includes ions such as carbonates and silicates. The titration method for determining total alkalinity was developed by (Dickson 1981). Research has demonstrated that both plants and microorganisms affect rock weathering, and the effects of microorganisms and plants should also be considered when assessing rock weathering rates (Swoboda, Döring, and Hamer 2022; Gerrits et al. 2020). Whereas K, P, Fe, Mg, and Ca ions carried in the rocks are continuously released with dissolution and migrate to the soil and crops, this may also be a means of replacing fertilizers (Barak, Chen, and Singer 1983). Dissolved materials released by weathering of minerals into the water column can increase the alkalinity of the water column, and these materials (primarily bicarbonates) are transported to the ocean by runoff and stored in stable form for 10,000 to 100,000 years (Renforth and Henderson 2017; Flipkens et al. 2023). Fig. 1 shows how rock powder removes CO_2 and improves soil.

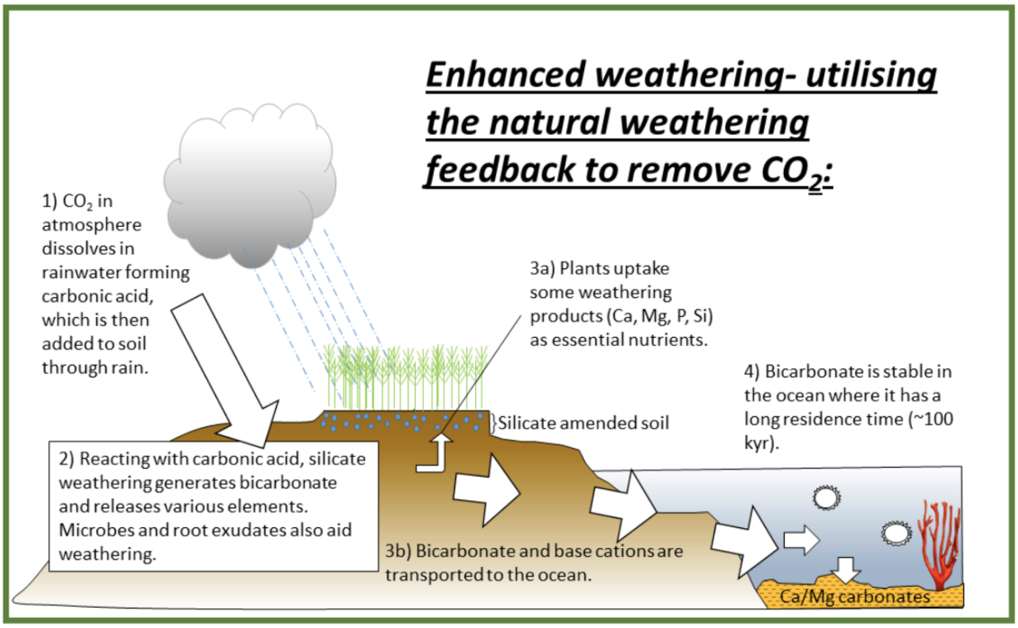

Fig. 1. Rock removes CO_2 and improves soil mechanism, from (Beerling et al. 2018) (Copyright 2018, Springer Nature).

The specific surface area is a crucial parameter in the chemical weathering of rocks. A larger surface area allows for greater contact between the rock and the chemical agents involved in the reaction, increasing the overall surface area available for reaction. ERW (explosive rock fragmentation) is a method of grinding rock to accelerate the weathering process. However, the size of the rock particles produced by this process is also a significant factor, influencing the efficiency of the ERW process as a whole. While it is feasible to grind rocks and minerals to exceedingly fine sizes, the financial and environmental costs associated with the grinding process tend to increase in proportion to the fineness of the resulting product. The energy requirements for grinding rock can be estimated using the Bond equation ：

$$W = 10W_i\left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right) \tag{5}$$

Where, W refers to the energy consumed, [kW h t^{-1}]; W_i refers to the work index of the material, [kW h t^{-1}]; P_{80} and F_{80} refers to the particle size, in micrometers, of 80% of the outgoing and incoming material passing through the grid, [μm].

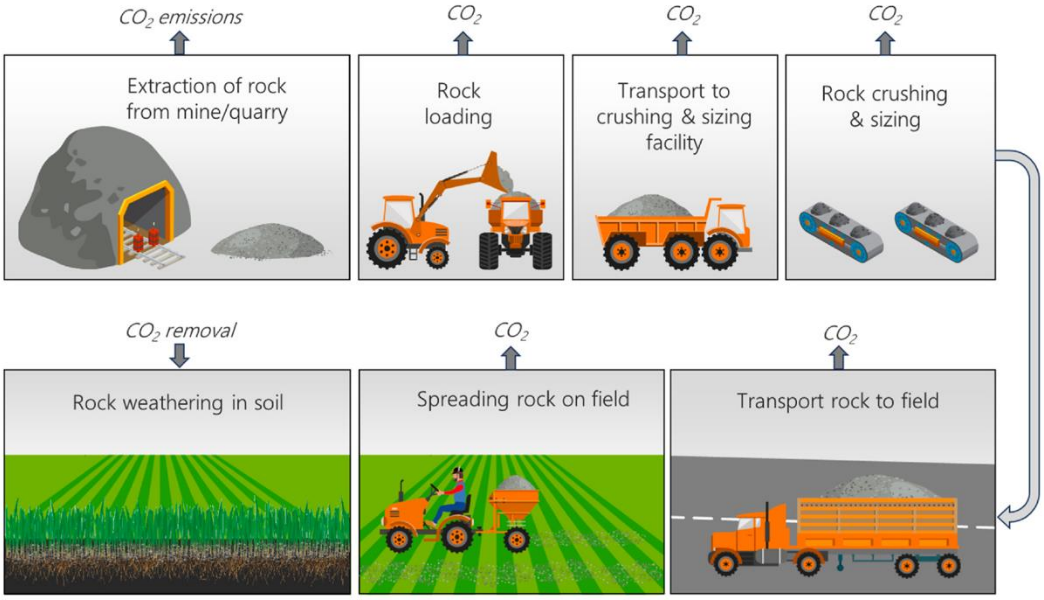

Fig. 2. The overall process of ERW, from (Jerden et al. 2024) (Copyright 2024, Elsevier).

The quantity of silicate powder utilized also has a considerable impact on the ultimate outcomes. Farmers in numerous regions have long employed the use of rock powders to enhance soil quality. However, there is currently no consensus regarding the optimal application rate of silicate rock powders, which has been observed to range from less than 1 t/ha to over 100 t/ha (Swoboda, Döring, and Hamer 2022). Theoretically, the greater the quantity of rock powder applied, the greater the number of ions released and the greater the amount of CO_2 sequestered. However, experimental evidence has demonstrated that the addition of excessive quantities of rock powder may have an inhibitory effect on CO_2 sequestration and crop growth. Consequently, the application rate must be adjusted to suit the specific characteristics of the region's soils, climate, temperature, and crops.

Enhanced weathering requires the least amount of land, and estimates of water required per ton of CO_2 removed by enhanced weathering are an order of magnitude lower than those for BECCS (bioenergy, carbon capture and storage) (Smith et al., 2016). Table 1 shows Global impacts of NETs for the average needed global C removals per year in 2100. This may facilitate the large-scale implementation of ERW, as ERW will have some positive effects on soils and crops, and the cost of synergies will be lower than that of capturing and sequestering CO_2. Despite the availability of experimental data, which has elucidated the role of numerous crucial parameters at both laboratory and field levels, it remains challenging to assess the precise amount of CO_2 fixation by ERW due to the intricate nature of the weathering process. This is a common challenge encountered by many NETs. Table 2 shows different NETs needs and benefits.

Table 2 Global impacts of NETs for the average needed global C removals per year in 2100 in 2°C-consistent scenarios, from (Smith et al. 2016)

NET	Global C removal (Gt Ceq yr-1in 2100)	Mean (max.) land requirement (Mha in 2100)	Estimated energy requirement (EJ yr-1 in 2100)	Mean (max.) water requirement (km3 yr-1 in 2100)	Nutrient impact(kt N yr-1 in 2100)	Albedo impact in 2100	Investment needs (BECCS for electricity/biofuel; US dollar yr-1 in 2050)
BECCS	3.3	380-700	-170	720	variable	variable	138 billion/123 billion
DAC	3.3	Very low (unless solar PV is used for energy)	156	10-300	none	none	>>BECCS
EW*	0.2(1.0)	2(10)	46	0.3(1.5)	none	none	>BECCS
AR*	1.1(3.3)	320(970)	Very low	370(1,040)	2.2(16.8)	Negative, or reduced GHG benefit where not negative	<<BECCS

*NET is with lower maximum potential than the BECCS emission requirement of 3.3Gt Ceq per year in 2100; their mean (and maximum potential is given along with their impacts (see Supplementary Methods). Wide ranges exist for most impacts; but for simplicity and to allow comparison between NETs.

3. Soil improvement in ERW

3.1 Soil pH

The improvement of soil pH is the initial indication of soil amelioration by ERW, as evidenced by studies conducted by (Blanc-Betes et al. 2021; Reershemius et al. 2023; Haque, Santos, and Chiang 2020b). The majority of experimental simulations and sites have acidic soils, with some exhibiting a soil pH approaching 3 (Dietzen, Harrison, and Michelsen-Correa 2018; Mersi, Kuhnert-Finkernagel, and Schinner,1992; Haque, Santos, and Chiang 2020; Taylor et al. 2021; Yan et al. 2023). It can be reasonably assumed that in such soils, the rate of rock dissolution is considerable, resulting in a notable increase in pH value. Additionally, the constant dissolution of rocks affects the soil by precipitating the ions that plants require, thereby enriching the soil with these essential elements (Guo et al. 2015; Kelland et al. 2020; Barak, Chen, and Singer 1983; Reis et al. 2024). Numerous studies have monitored the changes in soil pH before and after experiments, with final pH values varying depending on regional climate, temperature, precipitation, and the type of rock used. However, in all cases, an increase in pH was observed. This is likely because most experimental sites or indoor experiments utilized acidic soils. There are several advantages to this approach. Firstly, the weathering reaction proceeds more rapidly. Acidic environments typically accelerate the dissolution and weathering processes of minerals, as chemical reactions are more likely to occur when minerals, such as silicate minerals, come into contact with acidic solution. The low pH of acidic soils allows ERW to increase soil alkalinity, thereby improving soil quality. The alkaline substances released during rock weathering can neutralize soil acidity, enhancing soil fertility and providing a better growth environment for plants (Goulding 2016; Brantley 2008). Additionally, ERW in acidic soils aids in increasing the efficiency of CO_2 absorption. Under acidic conditions, CO_2 dissolves more readily in water to form carbonic acid, which then reacts with minerals in the rocks to form carbonates, thus achieving long-term CO_2 sequestration. This process can also improve soil structure and promote plant growth, thereby increasing the carbon sink capacity of the ecosystem. Wilfried von Mersi et al. evaluated the effects of low-dose rock powder (primarily a mixture of basalt and pyroxene) on forest soil life activity(Mersi, Kuhnert-Finkernagel, and Schinner,1992). After three years of field monitoring, the pH of soils in three different areas changed from 2.7, 4.9, and 3.4 to 3.0, 6.0, and 4.2, respectively. Christiana Dietzen et al. had also investigated the potential for enhancing soil pH and reducing carbon emissions through the application of silicate minerals (olivine was used in the study) in place of agricultural lime. A three-month experiment demonstrated that the objective of increasing soil pH was achieved, and the weathering rate was found to be lower in the high application olivine group than in the low application group (Dietzen, Harrison, and Michelsen-Correa 2018). The soil samples used in the experiment were collected from Nørholm Hede in southwestern Denmark, where the initial soil pH was 3.55. The study established different doses of olivine groups, OLIV Low and OLIV High, along with a lime treatment group and a control group. After 90 days, the final pH value of the control group was 3.56, while the OLIV Low treatment group had a pH of 4.69, the OLIV High treatment group had a pH of 5.18, and the lime treatment group had a pH of 6.06. The application of lime raised the soil pH by 2.51, whereas the OLIV High and OLIV Low treatments increased the pH by 1.63 and 1.13, respectively. In another study, Yongxue Yan and colleagues added wollastonite powder to 12 different types of soil samples from the subtropical regions of China, resulting in a significant increase in soil pH (an average of +2.78 pH units) over a 90-day experimental period(Yan et al. 2023). However, the study by Haque et al. yielded different results. After 56 days of field experiments, while the soil inorganic carbon (SIC) content increased, the soil pH remained unchanged (Haque, Santos, and Chiang 2020b). Direct comparisons between these experiments are challenging due to the numerous differing variables. For instance, Haque and Mersi’s experiments used wollastonite, while others employed olivine and basalt. The dissolution rates of different rocks vary, and the weathering conditions of the rock powders also differ, which could lead to divergent results. However, the differences in pH changes between field and laboratory experiments may exist. One major factor not accounted for in laboratory experiments is the influence of wind, which also plays a significant role in the weathering process. In field experiments, if the thickness of the rock powder layer is not substantial, factors like wind and rainfall will likely cause the rock powder to move from higher to lower elevations, potentially leading to discrepancies between the theoretical application rate and the actual applied amount. As a result, using the application rate to predict the final pH change could introduce inaccuracies. Fig. 3 shows the setup of most lab and field experiments, as well as the process.

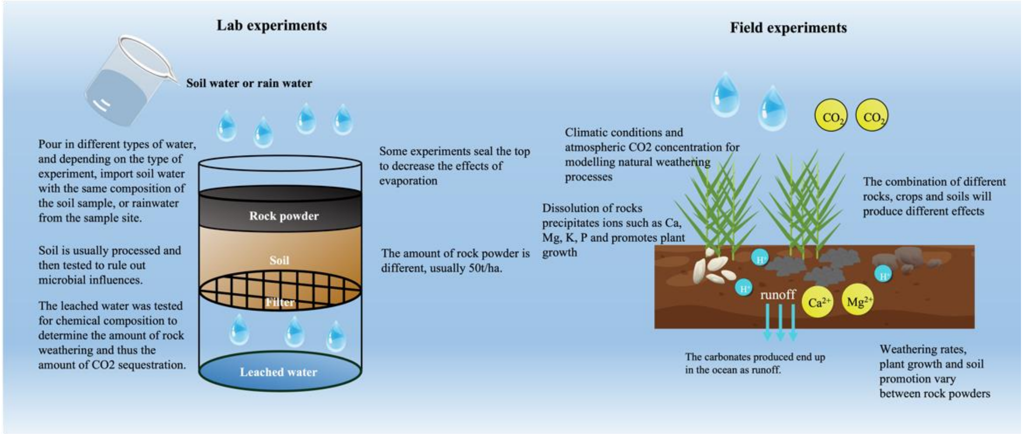

Fig. 3. Setup for lab experiments and field experiments.

3.2 Crop yield increase

When rock powders dissolve, they release essential alkaline cations such as Ca^{2+} and Mg^{2+}, as well as HCO3-. Some of these products may precipitate in the soil matrix as carbonate minerals. In addition to improving soil pH, ERW also provides additional nutrients to crops growing in the soil, due to increased availability of silicon and phosphorus, reduced nitrogen loss, and enhanced soil fertility (Beerling et al. 2020; 2018). Blanc-Betes et al. studied the application of basalt to bioenergy crops such as corn and Miscanthus to reduce N2O emissions. Their results showed that basalt application reduced N2O emissions by 16% and 9% in corn and Miscanthus, respectively, based on an improved DayCent model and three years of field observations (Blanc-Betes et al. 2021). Fengshan Guo and colleagues investigated the effect of basalt powder on carbon sequestration in phytoliths in rice fields. Their study found that the phytolith content in rice increased significantly with the amount of basalt powder applied, with a maximum increase of 150% (Guo et al. 2015). Phytoliths are tiny particles of silicate minerals that accumulate in plant cells, typically in the form of silica. These particles deposit within the plant cells, forming specific morphological structures that play a crucial role in plant growth and environmental adaptation. Due to the significant influence of factors such as soil type and rock type in ERW, it is difficult to make cross-comparisons when analyzing increases in crop yield. Kelland et al. found that applying basalt powder to sorghum crops significantly increased mature yields, primarily due to increased levels of potassium and phosphorus in the soil, which acted as fertilizers (Kelland et al. 2020). Although total inorganic carbon (TIC) in the soil showed little change, the levels of amino acid-extractable silicon and exchangeable magnesium increased significantly, while exchangeable calcium did not change significantly. The results also indicated that, in addition to increasing mature yields, basalt powder did not significantly increase the concentration of potentially toxic micronutrients in seeds. Hein F. M. ten Berge and colleagues investigated the effects of olivine weathering on the growth and nutrient uptake of ryegrass. Their experiment included seven treatment methods, with varying doses of olivine and two doses of magnesium-rich mineral brucite. The results showed that, in the group with the highest application rate, plant growth was 15.6% greater than in the control group, and the potassium concentration in plants was 16.5% higher (ten Berge et al. 2012). Fatima Haque et al. conducted a pot experiment on a rooftop at the University of Guelph in Canada, simulating the local climate conditions. The experiment included six pots: one with native soil, one with soil supplemented with wollastonite (MSA), and four with combinations of soybean and corn. The results indicated that adding wollastonite powder to the soil significantly increased the dry weight of soybean and corn after eight weeks, and also significantly increased the soil organic carbon content (Haque et al. 2019). However, the growth response differed between the two plants: soybean dry weight increased by 177%, while corn dry weight increased by 90%. The soybean biomass in MSA soil was 177% higher than in the control group, while corn height and biomass increased by 59% and 90%, respectively. These crop experiments provide new insights, but also raise some questions. For example, in some experimental groups, both nutrients and rock powders, or fertilizers and rock powders, were added simultaneously, making it difficult to determine which substance had the most impact on plant growth. Additionally, the nutrients provided by rock powders are much lower than those provided by fertilizers, but few experiments have directly compared rock powders with fertilizers. The advantage of ERW lies in its ability to improve soil, increase crop yields, and sequester CO_2 simultaneously. However, if the nutrient supply from rock powders is significantly lower than that from fertilizers, crop yields may not be adequately sustained.

3.3 Soil biota

Due to the limited number of experiments investigating the impact of ERW on soil microorganisms, the mechanisms involved remain somewhat unclear. Based on the existing experimental results, it appears that soil microorganisms and rock powders may have a mutually reinforcing relationship. On one hand, ERW can enhance the activity of certain microorganisms that decompose organic matter, increasing the decomposition rate of organic matter in the soil and thereby improving nutrient cycling efficiency. This, in turn, tends to enhance soil fertility and promote plant growth. On the other hand, soil microorganisms may accelerate the dissolution rate of rocks, thereby releasing more ions and absorbing more CO_2 (Olsson-Francis et al. 2012; Reis et al. 2024; Basak et al. 2017; Weber and Martinez 2017; Smith et al. 2016; Bi et al. 2024; 2024). The experiments by Olsson-Francis et al. demonstrated that cyanobacteria facilitated the dissolution of basalt powder with particle sizes smaller than 1 mm, as evidenced by the increased ion concentrations measured in the solution. Additionally, studies have found that acids have a significantly greater impact on rock dissolution in soil than organic matter does (Dontsova et al. 2014). However, there is currently a lack of experimental evidence showing the effectiveness of soil microorganisms in rock dissolution in the presence of organic acids. Sebastian Weber and colleagues suggested that certain inert soil biomass might buffer against carbonic acid, but its overall effect on weathering rates may be negligible. This indicates that in-situ experiments could be conducted to evaluate the weathering effects before applying rock powders to farmland or other land areas. Roqueto Reis and colleagues studied the impact of different silicate minerals (particularly rock dust) on soil plant communities. In addition to directly influencing soil chemical properties by providing minerals, rock dust also indirectly affects soil ecosystem functions by altering microbial communities and enzyme activities. The authors suggested that, considering soil formation, biological activity (i.e., living organisms) accelerates the transfer of chemical elements from the lithosphere to the biosphere (Reis et al. 2024). Mycorrhizal fungi, which form symbiotic relationships with many plants, have been shown to enhance mineral weathering by increasing the dissolution rate of silicates. These fungi are crucial in nutrient cycling, especially in nutrient-limited environments. Earthworms and other soil animals can alter the physicochemical properties of the soil, thereby affecting ERW. For example, earthworms can increase the bioavailability of nutrients through their digestive processes, which may further enhance weathering rates (Vicca et al. 2022). While spreading olivine powder in the ocean is another method, this review focuses solely on terrestrial ERW and will not cover marine applications. Nearly all experiments involving microorganisms have been conducted in laboratory settings, where microbial communities are easier to cultivate. While these experiments provide a broad perspective for evaluating ERW, additional field experiments are still needed to support data and enable a comprehensive evaluation of ERW.

All the soil improvement experiments and weathering experiments are summarized in Table 3 and Table 4 respectively.

Table 3 Soil improvement experiments

Rock Type	**Experiment Type**	**Experiment Time**	**Particle Size**	**Application Amount**	**CO_2 Sequestration**	**Authors**
Basalt	Pot	3 years	174 μm, 267 μm	4.8 t/ha, 2.5 t/ha	-	(Blanc-Betes et al. 2021)
Basalt	Pot	102 days	880 mm	2.8–27.8 t/ha	-	(Guo et al. 2015)
Basalt	Pot	120 days	1250 μm	100 t/ha	Soil CO_2 sequestration rate ranged from 2-4 tons CO_2/ha over 1-5 years.	(Kelland et al. 2020)
Basalt	Field	720 days	-	5–20 t/ha	-	(Anda, Shamshuddin, and Fauziah 2013)
Basalt	Pot	120 days	100–1000 μm	0.5–5.6 t/ha	-	(Barak, Chen, and Singer 1983)
Olivine, Basalt, Wollastonite	Pot	64 days	-	0.125:1	Wollastonite: 0.61-0.63 g CO_2/kg soil, Olivine: 0.60-0.58 g CO_2/kg soil, Basalt: 0.10-0.12 g CO_2/kg soil.	(te Pas, Hagens, and Comans 2023)
Olivine	Pot	224 days	66% 2-50 μm, 27% 50-200 μm	1.63 t/ha, 204 t/ha	High dose: 2.69 t/ha, Low dose: 0.29 t/ha in 224 days.	(ten Berge et al. 2012)
Wollastonite	Pot	90 days	<50 μm	0.1:1	-	(Yan et al. 2023)
Wollastonite	Field	56 days	90% <25.9 μm	0.125:1	47.4 kg CO_2/ha/year	(Haque et al. 2019)
Wollastonite	Field	98 days	90% <63.7 μm	30-400 t/ha	0.08 kg CO_2/m^2/month	(Haque, Santos, and Chiang 2020b)

Basalt and Other Mixtures	Field	3 years	-	34.1 t/ha	-	(Mersi, Kuhnert-Finkernagel, and Schinner, 1992)
Olivine	Pot	90 days	20 µm	0.008:1, 0.04:1	High dose: 4.16 t/ha, Low dose: 3.13 t/ha in three months.	(Dietzen, Harrison, and Michelsen-Correa 2018)
Wollastonite	Pot	3 years	90% < 83.7 µm, 63.7 µm, 4.4 ± 0.06 µm	1.5-5 t/ha	0.079 t/ha/month	(Haque, Santos, and Chiang 2020a)
Basalt and Other Rocks	Pot	240 days	50% 0.1–0.05 mm, 25% 0.5–0.25 mm, 25% 2–1 mm	1 t/ha	-	(Reis et al. 2024)
Volcanic rock	Field	Over 3 years	80%=1767µm	50 t/ha	3.8 t/ha/year	(Larkin et al. 2022)
Basalt	Pot	99 days	-	50 t/ha	1.83 t/ha 1year - 4.48 t/ha 5years	(Vienne et al. 2022)
Wollastonite	Field	15 years	<16 µm	3.44 t/ha	0.025–0.13 t /ha 15years	(Taylor et al. 2021)

Table 4 Weathering experiments

Rock Type	Experiment Time	Particle Size	Application Rate	CO_2 Sequestration Rate	Authors
Basalt, Olivine	60 days	104–150 µm, after ball milling <10 µm	2 g/L	16.6 g CO_2: 1 g mixture	(Rigopoulos et al. 2018)
Basalt	14 days	14.1–47.2 µm	50 t/ha	2.4-4.5 t CO_2/ha/year and 11.9 t CO_2/ha/year	(Ryan et al. 2024)
Basalt, Olivine	14 days	9.96–10.3 µm, 32.2–60 µm, 265.4–502.4 µm	50 t/ha	6.5 t/ha/year and 6.8 t/ha/year	(Vanderkloot and Ryan 2023)
Basalt	19 days	<2mm	-	-	(Dontsova et al. 2014)
Olivine	225 days	80% > 125 µm	127 t/ha	-	(Pogge Von Strandmann et al. 2022)
Olivine	70 days	126–216 µm	-	-	(Flipkens et al. 2023)
Olivine	18 days	40–63 µm	-	-	(Weber and Martinez 2017)
Olivine, Basalt	300 days	0.5–3200 µm	-	-	(Amann et al. 2022)
Wollastonite	380 days	52 µm	-	145 kg CO_2/t/year	(Stubbs et al. 2023)

4. Carbon sequestration in ERW

4.1 Application amount and grain size

The application rate and particle size of rocks have a significant impact on ERW, as demonstrated in most experiments. The specific application rates and particle sizes used in the experiments are summarized in the table from the previous section. This part focuses on the effects of these two variables on CO_2 sequestration.

Firstly, regarding the application rate: Theoretically, the more rock powder applied, the more alkaline cations will be released during rock dissolution and weathering, which would lead to greater CO_2 sequestration. However, the actual experimental results differ. For instance, in an experiment conducted by Christiana Dietzen, where olivine powder was applied to acidic soil, the dissolution rate of rocks in the high application rate group (0.04 g olivine: 1 g soil) was only 7.1% (Dietzen, Harrison, and Michelsen-Correa 2018). Similar results were recorded in the experiment by(ten Berge et al. 2012). It seems that there is an upper limit to the amount of rock powder that can be dissolved effectively in soils and ecosystems. Once this limit is exceeded, negative feedback may occur. As the rock dissolves, organic acids in the soil are continuously consumed, leading to a stabilization of the dissolution rate, with excess rock powder failing to participate in the reaction. The formation of various acids in the soil takes time, and an excessive amount of rock powder may disrupt the natural soil environment. Another possible explanation is that micro-scale experiments in the laboratory may amplify design flaws. For example, many experiments use cylindrical devices for soil column experiments, layering rocks and soil. This can lead to a situation where the soil and rock at the device boundaries do not fully integrate, preventing complete reactions. This issue is less relevant in field experiments, where the field can be considered as having an infinitely extended boundary.

The particle size of the rock also affects the reaction rate. The larger the specific surface area of the rock, the greater the area available for reaction, which theoretically speeds up the reaction; in other words, finer powder results in a faster weathering rate (Rigopoulos et al. 2018; Vanderkloot and Ryan 2023; Amann et al. 2022; Ryan et al. 2024; Flipkens et al. 2023). Most experiments measure the particle size distribution of the rocks used. However, the grinding process does not produce precisely categorized particle sizes but rather a collection of particles with a range of sizes. This makes it difficult to precisely compare results across different experiments. Many researchers suggest that the ground particles can be considered to follow a normal distribution, and in future experiments, this approach could be used to quantify particle size as a variable (Cepuritis et al. 2017; Petavratzi, Kingman, and Lowndes 2005; Strefler et al. 2018).

4.2 CO_2 value calculation

Accurately calculating the amount of CO_2 sequestered is crucial for better and more effective evaluation of the benefits brought by ERW. In ERW experiments, almost all CO_2 quantification methods are based on measuring the ionic flux after rock reactions (Kelland et al. 2020; Reershemius et al. 2023; Ryan et al. 2024; 2024; Haque, Santos, and Chiang 2020a; 2020b; Dietzen, Harrison, and Michelsen-Correa 2018; Amann et al. 2022; Blanc-Betes et al. 2021; Taylor et al. 2021; Larkin et al. 2022).

Typically, the amount of rock reacted is calculated by measuring the fixed ion concentrations, and then the CO_2 consumption is calculated based on the reaction equations. This approach is common in laboratory experiments. For example, in certain studies, the liquid collected from each leaching event in soil column experiments is analyzed for Mg^{2+} concentration, which is then used to estimate the amount of CO_2 reacted. This method is currently the mainstream approach. Tom Reershemius and colleagues, building on Kelland’s experiment, developed the Ti-CAT mass balance method and compared it with previous results(Reershemius et al. 2023). The results were nearly identical, but in terms of measurement convenience and economic efficiency, the Ti-CAT method proved superior. This method involves directly measuring the concentration of Ni ions in the soil and leachate, thus eliminating interference from soil and other factors. However, this method may not be suitable for wollastonite. Another approach involves calculating the changes in total alkalinity in the soil solution, which is similar to the Mg^{2+} measurement method. Additionally, data from laboratory experiments can be input into PHREEQC (a powerful geochemical modeling software developed by the U.S. Geological Survey) to simulate the long-term CO_2 sequestration potential of ERW over extended time scales (Kelland et al. 2020; Vienne et al. 2022).

Some researchers believe that the measurement of CO_2 sequestration in laboratory experiments may be underestimated because as water flows from the top to the bottom of the experimental system, some ions adhere to the intermediate soil layers, known as capillary water(Ryan et al. 2024; Vanderkloot and Ryan 2023; Vienne et al. 2022). Capillary water can also contain ions that need to be measured, leading to smaller final measurements and thus an underestimation of CO_2 sequestration. However, this view seems to be somewhat inaccurate. Soil is a product of weathering, and after prolonged exposure to the atmosphere, it is supposed that the substances in the soil have reached equilibrium with CO_2 in water and air. However, the soil still contains substances that can react with acids. Considering this, the actual amount of CO_2 reacted may be overestimated. Researchers must ensure that the amount of soil reacting with acids is known, but this can be challenging in practice. For instance, it is difficult to determine whether the acid solution reacts with the minerals in the soil or with the rock powder first.

Beerling et al. developed a model of basalt dissolution, taking into account the varying composition of particles with soil depth and time(Beerling et al. 2020). They also considered the chemical inhibition of dissolution as pore fluids approach phase equilibrium with reactive basalt minerals, as well as the formation of soil-forming calcium carbonate minerals in equilibrium with pore fluids. The first is the transfer equation, in which the state variable calculated is the dissolved molar equivalent of the element released by the dissolution of some mineral stoichiometry.

By subtracting the crop evapotranspiration (Siebert and Doell 2010) from the annual net water volume obtained through precipitation and irrigation, it is possible to estimate the weathering rates of ERW over several decades using available rainfall and irrigation data. This allows for the prediction of long-term ERW weathering outcomes and the determination of theoretical CO_2 sequestration values based on specific rock and mineral laboratory experiments.

4.3 Laboratory and field monitoring of CO_2 fluxes

In addition to the calculation of ion concentrations in ERW experiments, it is also important to monitor CO_2 fluxes in the experiment or in the field. In lab experiments, CO_2 fluxes are most commonly monitored using an infrared gas analyzer, which has the advantage of monitoring CO_2 concentrations in real time to calculate fluxes(Taylor et al. 2021; Vienne et al. 2022). In field experiments, a common approach is to calculate CO_2 fluxes from soil and gas samples, which can be extrapolated to the entire area(Larkin et al. 2022; Mersi, Kuhnert-Finkernagel, and Schinner, 1992).

Larkin's study conducted site CO_2 monitoring at an oil palm plantation in Malaysia, the first such field experiment on enhanced weathering in the tropics(Larkin et al. 2022). The study assessed the effectiveness of CO_2 removal through alkalinity generation by continuously monitoring chemical changes in soil and streams. Specific methods included: (1) measuring the alkalinity and flow rate of stream waters to quantify CO_2 removal due to alkalinity generation by calculating the equivalent concentration of CO_2 and water flow rate; (2) using soil core samples to analyze changes in soil chemistry, particularly carbonate content, to assess the contribution of carbonate formation to CO_2 capture; (3) analyzing soil chemistry to assess the effect of carbonate formation on CO_2 removal.

Taylor's study used gas collection chambers to monitor CO_2 fluxes from soils by setting up monitoring sites at multiple elevations(Taylor et al. 2021). Since 2002, researchers have installed PVC rings at multiple fixed locations in treated and reference watersheds and have periodically collected gas samples from collection chambers on these rings. Due to the non-normal distribution of the data, the study analyzed the results using the Kruskal-Wallis test with a significance level of 0.05. To further assess the effectiveness of the treatments, the study also compared inorganic carbon fluxes carried by water flow through the streams and calculated inorganic CO_2 depletion by bicarbonate flow. The experimental results showed that after 15 years of treatment, the inorganic CO_2 consumption in the treated watershed increased significantly to twice that of the reference watershed, indicating a significant carbon capture effect of the treatment.

Vienne measured CO_2 fluxes by first assuming a constant atmospheric CO_2 concentration of 414 ppm and converting the CO_2 concentration in the soil at different depths to a pressure based on the average soil temperature of the experiment (285 K) (Vienne et al. 2022). Measurements were made through a customized soil chamber connected to a portable infrared gas analyzer (EGM-5). Changes in CO_2 concentration in the soil were recorded during measurements until a concentration difference of 50 ppm was reached, or for a continuous measurement of 120 seconds. The CO_2 concentration difference in the soil increased with depth and Fick's law was utilized to calculate the CO_2 flux. The flux of CO_2 was also evaluated by measuring the water-filled porosity of the soil and other relevant parameters, combining the experimental data with the simulation results to provide a comprehensive assessment of the flux of CO_2.

5. Costs, environmental risks and outlook

5.1 Costs

In the mechanism section, all the processes involved in ERW. Therefore, the costs associated with ERW can be calculated using the following formula (Kantzas et al. 2022):

$$\mathrm{Costs}(\mathrm{y},\mathrm{p80}) = \sum\nolimits_{\mathrm{Locations}} \frac{\mathrm{Min}(y)+\mathrm{Grind}(y,\mathrm{p80})+\mathrm{Transp}(y,\mathrm{loc})+\mathrm{Spread}(y)-\mathrm{P}(y,\mathrm{p80},\mathrm{loc})-\mathrm{K}(y,\mathrm{p80},\mathrm{loc})}{\mathrm{CO_2\ Gross\ Seq}\ (y,\mathrm{p80},\mathrm{loc})-\mathrm{CO_2\ Secondary\ Emissions}\ (y,\mathrm{p80},\mathrm{loc})} \quad (6)$$

Where, Costs are the annual cost of ERW, [£ t CO_2^{-1}]; y represents the year; $\mathrm{p80}$ is the power consumption per ton of ground rock is a function of particle size (Beerling et al. 2020); the release of P and K depends on the year, $\mathrm{p80}$, and location, as both particle size and environmental factors (such as climate) influence weathering rates, which in turn affect the release of these elements.; Min and Spread costs are functions of the year, as the application rate was the same for all locations; Grind costs are a function of the year and $\mathrm{p80}$; Transp costs are function of the year and location, and consider the distance from the rock source.

Calculating the economic viability of ERW requires assessing both the cost of emissions reduction and the amount of CO_2 sequestered, making accurate CO_2 sequestration measurements essential. A simplified cost calculation model can directly estimate the costs related to mining and distributing rock, emissions generated during ERW treatment, and the potential benefits of CO_2 sequestration.

Life Cycle Assessment (LCA) offers a comprehensive method for evaluating the environmental impacts of a product, process, or service throughout its entire lifecycle, from raw material extraction to final disposal. This "cradle-to-grave" approach is widely used by researchers to assess ERW, contributing significantly to decision-making and budgeting for the technology (Schopka, Derry, and Arcilla 2011; Zhou 2024; Jerden et al. 2024; Lefebvre et al. 2019). LCA also helps identify the variables that most affect overall costs, providing a clearer focus for improving efficiency. James Jerden and his team, using Stella Architect software, modeled the entire ERW process, factoring in variables like rock powder particle size, soil pH, temperature, and biological weathering (Jerden et al. 2024). Their simulation, applied to a Brazilian farm, yielded results consistent with lab and field test data. Sensitivity analysis of the model predicted a CDR rate for basalt and olivine between 1 and 10 t CO_2/ha over ten years, depending on conditions. If scaled to cover 25% to 75% of Brazil's farmland, the model projected CO_2 reductions of 0.18 Gt and 0.53 Gt, respectively, over a decade. These variables have a substantial impact on the efficiency and cost of ERW.

In another study, David Lefebvre's team used LCA to evaluate ERW and concluded that long-distance transportation significantly affects its overall feasibility (Lefebvre et al. 2019). Qiyu Zhou explored the use of basalt sand on U.S. golf courses, a potential CO_2 capture strategy. Traditionally, quartz sand is used, but substituting basalt sand could serve dual purposes: turf coverage and CO_2 sequestration. Zhou reviewed studies on how factors like temperature, pH, and particle size influence basalt dissolution, concluding that under favorable conditions (such as temperatures above 25°C and pH near 8.5), basalt sand applied to an 18-hole course could sequester at least 4,200 tons of CO_2 annually, potentially reaching 115,600 tons when scaled to all golf courses nationwide. However, transportation emissions would offset some of these benefits (Zhou 2024).

Such research underlines the importance of ensuring that NETs like ERW are developed with a focus on minimizing CO_2 emissions throughout their implementation. These technologies must balance cost-effectiveness with their primary goal of reducing emissions. Only by achieving this balance can global emissions targets become attainable. Importantly, CO_2 sequestration technologies should never result in net increases in emissions.

5.2 Environmental risk

ERW presents potential environmental risks, as highlighted in numerous laboratory studies (Anda, Shamshuddin, and Fauziah 2013; Amann et al. 2020; Rijnders et al. 2023; Dietzen, Harrison, and Michelsen-Correa 2018; Flipkens et al. 2023). Basalt and olivine, both commonly used in ERW, contain heavy metals, raising concerns about the release of metal ions like nickel (Ni) and chromium (Cr) into the soil during weathering and dissolution. Multiple studies have detected elevated levels of Ni in soil solutions and leachates when olivine powder is used, calling into question the feasibility of employing olivine and peridotite in large-scale ERW applications (Choi et al. 2021; Yu et al. 2024).

Ni, a siderophile element, has a strong affinity for iron and can substitute for magnesium and iron within the olivine crystal structure. Due to this property, olivine tends to accumulate Ni during its formation in the Earth's mantle, where Ni concentrations are relatively high. Similarly, Cr accumulates in olivine. In contrast, basalt's mineral composition generally results in lower metal contamination, making it a potentially safer choice for ERW. As cations from rock dissolution enter groundwater, they may eventually reach the ocean (Beerling et al. 2020; Abdalqadir et al. 2024; Coogan and Dosso 2015). Ni and Cr pose significant risks to marine ecosystems by disrupting ion regulation, inducing respiratory toxicity, and causing oxidative stress. Once in the ocean, these metals can cycle between the water column and sediments through processes like adsorption, diffusion, and bioturbation, with sediments often acting as long-term reservoirs. Marine organisms may ingest these heavy metals through contaminated food or sediments, leading to toxic effects (Flipkens et al. 2023).

On land, the accumulation of Ni and Cr can result in soil contamination, which may extend to the food chain, impacting the broader ecological environment (Choi et al. 2021). In addition, many silicate minerals used in ERW contain aluminum (Al), which can be converted into toxic Al^{3+} under acidic conditions. This poses risks to plants, microorganisms, and the overall soil ecosystem, especially in regions experiencing soil acidification. Therefore, careful consideration of the risks associated with Al^{3+} release is necessary when planning ERW applications.

5.3 Outlook

Although ERW has made significant strides in both laboratory and field experiments, many challenges remain unresolved. This section will discuss the technical issues across the ERW process and suggest future research directions.

One of the key challenges is the disparity between weathering rates observed in laboratory settings versus field conditions. Laboratory experiments provide valuable theoretical insights, but field experiments are essential for evaluating the real-world applicability of ERW. In the lab, many factors influencing rock dissolution and weathering can be controlled or isolated, enabling focused studies of specific variables. For instance, laboratory experiments may compare the weathering behavior of the same rock in different soils or assess the carbon sequestration efficiency of various rocks in identical soil conditions. However, these controlled environments come with limitations. The most critical is that laboratory setups lack the complexity of natural environments, such as the impact of wind on rock powder dispersion. To address this, field experiments should include more comprehensive monitoring, not only within the experimental area but also in adjacent regions, to better understand ERW's broader impacts. Given the slow rate of rock weathering due to the low partial pressure of CO_2 in the atmosphere, this process can take decades or centuries. Therefore, understanding the fundamental principles as early as possible is essential to meeting emission reduction goals within this century.

Climate conditions, including temperature and precipitation, also play a significant role in ERW field experiments. Water is crucial as it facilitates the conversion of CO_2 into reactive ions like H^+ and CO_3^{2-}. In ERW experiments, water availability varies significantly. Some studies keep soil at a constant humidity to support microorganism growth, but this differs from natural rainfall conditions. Whether these controlled conditions produce results that can be replicated under natural precipitation is an open question. Experiments should aim to mirror natural conditions as closely as possible.

Another challenge lies in the formation of secondary minerals when rock powder interacts with soil in natural environments. The development of these minerals is influenced by factors such as soil pH, temperature, and pressure. Future research should focus on understanding the mechanisms by which secondary minerals form under different environmental conditions, as this knowledge is crucial for advancing ERW. For example, basalt exhibits a V-shaped dissolution curve, indicating a substantial dissolution rate even in alkaline conditions. Alkaline environments may also promote the formation of calcite, which helps stabilize CO_2. While this concept has been explored in geological CO_2 sequestration, it remains under-researched in ERW.

Additionally, comparative studies in similar climatic zones but with different soil types could help clarify the role of specific soils in ERW processes. Rock powders can enhance soil nutrients and improve crop yields, raising the question of whether they could replace traditional fertilizers. This is an urgent area of inquiry, and further experiments comparing the effects of rock powders and fertilizers on plant growth are needed.

Despite its potential to mitigate climate change, ERW also poses risks. Large-scale application could alter soil chemistry, potentially affecting agriculture and ecosystems. Economically, high costs, a lack of commercial incentives, and insufficient policy support present significant barriers. Thus, while ERW holds promise, its long-term effectiveness, sustainability, and underlying mechanisms require further research and refinement.

6. Conclusion

The following conclusions were drawn through a critical review of experiments in ERW：

1. The CO_2 sequestration capacity of ERW technology is influenced by multiple factors, including soil type, rock type, application rate, and particle size. Different types of soils and rocks exhibit significant variations in their CO_2 absorption and fixation efficiency during the weathering process. While theoretically, higher application rates and smaller particle sizes should increase CO_2 sequestration efficiency, excessive application may reduce the efficiency of the weathering reactions and could even have adverse effects. Additionally, the differences between laboratory conditions and actual environmental conditions make the accurate estimation of CO_2 sequestration amounts complex.
2. ERW technology can significantly improve soil pH, especially in acidic soils, by neutralizing soil acidity and enhancing soil quality. Experiments have shown that applying rock powders such as basalt and olivine in different acidic soils effectively increases soil pH, promoting the release of alkaline substances in the soil, thus providing a more favorable environment for plant growth. However, the changes in pH observed in laboratory experiments may differ from those in field experiments, necessitating further on-site studies under various environmental conditions to verify these results.
3. ERW technology has shown potential in experiments to increase crop yields, mainly due to the release of alkaline cations such as Ca^{2+} and Mg^{2+} during the weathering process, as well as the increased availability of silicon and phosphorus in the soil. However, different types of crops respond differently to ERW, with some showing more significant yield increases under specific conditions. Moreover, differences in the type of rock used, application methods, and environmental conditions across various experiments make it challenging to directly compare results across studies.
4. The large-scale application of ERW technology faces significant economic challenges and potential environmental risks. The high costs associated with mining, grinding, and transporting rock materials may limit its commercial viability. Additionally, the release of heavy metals such as Ni and Cr during rock weathering could contaminate soil and water bodies, particularly when large quantities of olivine are used. Long-term environmental monitoring and risk assessment are essential to ensure the safety and sustainability of ERW practices.
5. Future research should focus on long-term field experiments to better understand the performance of ERW technology in real-world environments. Additionally, studying the mechanisms of secondary mineral formation during rock weathering, as well as the influence of climate and soil on ERW, is crucial for improving CO_2 sequestration efficiency and environmental safety. This will aid in optimizing ERW application strategies, making them more efficient and sustainable while minimizing potential environmental risks.

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References

Abdalqadir, Mardin, David Hughes, Sina Rezaei Gomari, and Ubaid Rafiq. 2024. “A State of the Art of Review on Factors Affecting the Enhanced Weathering in Agricultural Soil: Strategies for Carbon Sequestration and Climate Mitigation.” *ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH* 31 (13): 19047–70. https://doi.org/10.1007/s11356-024-32498-5.

Amann, Thorben, Jens Hartmann, Roland Hellmann, Elisabete Trindade Pedrosa, and Aman Malik. 2022. “Enhanced Weathering Potentials—the Role of in Situ CO2 and Grain Size Distribution.” *Frontiers in Climate* 4 (July):929268. https://doi.org/10.3389/fclim.2022.929268.

Amann, Thorben, Jens Hartmann, Eric Struyf, Wagner de Oliveira Garcia, Elke K. Fischer, Ivan Janssens, Patrick Meire, and Jonas Schoelynck. 2020. “EnhancedWeathering and Related Element Fluxes - a Cropland Mesocosm Approach.” *BIOGEOSCIENCES* 17 (1): 103–19. https://doi.org/10.5194/bg-17-103-2020.

Anda, Markus, J. Shamshuddin, and C. I. Fauziah. 2013. “Increasing Negative Charge and Nutrient Contents of a Highly Weathered Soil Using Basalt and Rice Husk to Promote Cocoa Growth under Field Conditions.” *SOIL & TILLAGE RESEARCH* 132 (August):1–11. https://doi.org/10.1016/j.still.2013.04.005.

Barak, Phillip, Yona Chen, and Arieh Singer. 1983. “Ground Basalt and Tuff as Iron Fertilizers for Calcareous Soils.” *Plant and Soil* 73 (1): 155–58. https://doi.org/10.1007/BF02197765.

Basak, B. B., B. Sarkar, D. R. Biswas, S. Sarkar, P. Sanderson, and R. Naidu. 2017. “Bio-Intervention of Naturally Occurring Silicate Minerals for Alternative Source of Potassium: Challenges and Opportunities.” In *ADVANCES IN AGRONOMY, VOL 141*, edited by D. L. Sparks, 141:115–45. San Diego: Elsevier Academic Press Inc. https://doi.org/10.1016/bs.agron.2016.10.016.

Beerling, David J., Euripides P. Kantzas, Mark R. Lomas, Peter Wade, Rafael M. Eufrasio, Phil Renforth, Binoy Sarkar, et al. 2020. “Potential for Large-Scale CO2 Removal via Enhanced Rock Weathering with Croplands.” *Nature* 583 (7815): 242–48. https://doi.org/10.1038/s41586-020-2448-9.

Beerling, David J., Jonathan R. Leake, Stephen P. Long, Julie D. Scholes, Jurriaan Ton, Paul N. Nelson, Michael Bird, et al. 2018. “Farming with Crops and Rocks to Address Global Climate, Food and Soil Security.” *Nature Plants* 4 (3): 138–47. https://doi.org/10.1038/s41477-018-0108-y.

Berge, Hein F. M. ten, Hugo G. van der Meer, Johan W. Steenhuizen, Paul W. Goedhart, Pol Knops, and Jan Verhagen. 2012. “Olivine Weathering in Soil, and Its Effects on Growth and Nutrient Uptake in Ryegrass (*Lolium Perenne* L.): A Pot Experiment.” *PLoS ONE* 7 (8): e42098. https://doi.org/10.1371/journal.pone.0042098.

Bi, Boyuan, Guochen Li, Daniel S. Goll, Luxiang Lin, Hui Chen, Tongtong Xu, Qiong Chen, et al. 2024. “Enhanced Rock Weathering Increased Soil Phosphorus Availability and Altered Root Phosphorus-Acquisition Strategies.” *GLOBAL CHANGE BIOLOGY* 30 (5): e17310. https://doi.org/10.1111/gcb.17310.

Blanc-Betes, Elena, Ilsa B. Kantola, Nuria Gomez-Casanovas, Melennie D. Hartman, William J. Parton, Amy L. Lewis, David J. Beerling, and Evan H. DeLucia. 2021. “In Silico Assessment of the Potential of Basalt Amendments to Reduce N_2O Emissions from Bioenergy Crops.” *GLOBAL CHANGE BIOLOGY BIOENERGY* 13 (1): 224–41. https://doi.org/10.1111/gcbb.12757.

Brantley, Susan L. 2008. “Kinetics of Mineral Dissolution.” In *Kinetics of Water-Rock Interaction*, edited by Susan L. Brantley, James D. Kubicki, and Art F. White, 151–210. New York, NY: Springer New York. https://doi.org/10.1007/978-0-387-73563-4_5.

Cepuritis, Rolands, Edward J. Garboczi, Chiara F. Ferraris, Stefan Jacobsen, and Bjorn E. Sorensen. 2017. “Measurement of Particle Size Distribution and Specific Surface Area for Crushed Concrete Aggregate Fines.” *ADVANCED POWDER TECHNOLOGY* 28 (3): 706–20. https://doi.org/10.1016/j.apt.2016.11.018.

Choi, Woo-Jung, Hyun-Jin Park, Yanjiang Cai, and Scott X. Chang. 2021. “Environmental Risks in Atmospheric CO_2 Removal Using Enhanced Rock Weathering Are Overlooked.” *ENVIRONMENTAL SCIENCE & TECHNOLOGY* 55 (14): 9627–29. https://doi.org/10.1021/acs.est.1c02505.

Coogan, Laurence A., and Stan E. Dosso. 2015. “Alteration of Ocean Crust Provides a Strong Temperature Dependent Feedback on the Geological Carbon Cycle and Is a Primary Driver of the Sr-Isotopic Composition of Seawater.” *Earth and Planetary Science Letters* 415 (April):38–46. https://doi.org/10.1016/j.epsl.2015.01.027.

Dickson, A. G. 1981. “An Exact Definition of Total Alkalinity and a Procedure for the Estimation of Alkalinity and Total Inorganic Carbon from Titration Data.” *Deep Sea Research Part A. Oceanographic Research Papers* 28 (6): 609–23. https://doi.org/10.1016/0198-0149(81)90121-7.

Dietzen, Christiana, Robert Harrison, and Stephani Michelsen-Correa. 2018. “Effectiveness of Enhanced Mineral Weathering as a Carbon Sequestration Tool and Alternative to Agricultural Lime: An Incubation Experiment.” *INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL* 74 (July):251–58. https://doi.org/10.1016/j.ijggc.2018.05.007.

Dontsova, Katerina, Dragos Zaharescu, Whitney Henderson, Sarah Verghese, Nicolas Perdrial, Edward Hunt, and Jon Chorover. 2014. “Impact of Organic Carbon on Weathering and Chemical Denudation of Granular Basalt.” *GEOCHIMICA ET COSMOCHIMICA ACTA* 139 (August):508–26. https://doi.org/10.1016/j.gca.2014.05.010.

Eufrasio, Rafael M., Euripides P. Kantzas, Neil R. Edwards, Philip B. Holden, Hector Pollitt, Jean-Francois Mercure, S. C. Lenny Koh, and David J. Beerling. 2022. “Environmental and Health Impacts of Atmospheric CO2 Removal by Enhanced Rock Weathering Depend on Nations’ Energy Mix.” *Communications Earth & Environment* 3 (1): 1–13. https://doi.org/10.1038/s43247-022-00436-3.

Flipkens, Gunter, Michael Fuhr, Geraldine Fiers, Filip J. R. Meysman, Raewyn M. Town, and Ronny Blust. 2023. “Enhanced Olivine Dissolution in Seawater through Continuous Grain Collisions.” *GEOCHIMICA ET COSMOCHIMICA ACTA* 359 (October):84–99. https://doi.org/10.1016/j.gca.2023.09.002.

Gerrits, R., R. Pokharel, R. Breitenbach, J. Radnik, I. Feldmann, J. A. Schuessler, F. von Blanckenburg, A. A. Gorbushina, and J. Schott. 2020. “How the Rock -Inhabiting Fungus K. Petricola A95 Enhances Olivine Dissolution through Attachment.” *GEOCHIMICA ET COSMOCHIMICA ACTA* 282 (August):76–97. https://doi.org/10.1016/j.gca.2020.05.010.

Goulding, K. W. T. 2016. “Soil Acidification and the Importance of Liming Agricultural Soils with Particular Reference to the United Kingdom.” Edited by Amarilis De Varennes. *Soil Use and Management* 32 (3): 390–99. https://doi.org/10.1111/sum.12270.

Guo, Fengshan, Zhaoliang Song, Leigh Sullivan, Hailong Wang, Xueyan Liu, Xudong Wang, Zimin Li, and Yuying Zhao. 2015. “Enhancing Phytolith Carbon Sequestration in Rice Ecosystems through Basalt Powder Amendment.” *SCIENCE BULLETIN* 60 (6): 591–97. https://doi.org/10.1007/s11434-015-0729-8.

Haque, Fatima, Rafael M. Santos, and Yi Wai Chiang. 2020a. “CO_2 Sequestration by Wollastonite-Amended Agricultural Soils - An Ontario Field Study.” *INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL* 97 (June):103017. https://doi.org/10.1016/j.ijggc.2020.103017.

———. 2020b. “Optimizing Inorganic Carbon Sequestration and Crop Yield With Wollastonite Soil Amendment in a Microplot Study.” *FRONTIERS IN PLANT SCIENCE* 11 (July):1012. https://doi.org/10.3389/fpls.2020.01012.

Haque, Fatima, Rafael M. Santos, Animesh Dutta, Mahendra Thimmanagari, and Yi Wai Chiang. 2019. “Co-Benefits of Wollastonite Weathering in Agriculture: CO_2 Sequestration and Promoted Plant Growth.” *ACS OMEGA* 4 (1): 1425–33. https://doi.org/10.1021/acsomega.8b02477.

Hartmann, Jens, A. Joshua West, Phil Renforth, Peter Köhler, Christina L. De La Rocha, Dieter A. Wolf-Gladrow, Hans H. Dürr, and Jürgen Scheffran. 2013. “Enhanced Chemical Weathering as a Geoengineering Strategy to Reduce Atmospheric Carbon Dioxide, Supply Nutrients, and Mitigate Ocean Acidification.” *Reviews of Geophysics* 51 (2): 113–49. https://doi.org/10.1002/rog.20004.

Hilton, Robert G., and A. Joshua West. 2020. “Mountains, Erosion and the Carbon Cycle.” *NATURE REVIEWS EARTH & ENVIRONMENT* 1 (6): 284–99. https://doi.org/10.1038/s43017-020-0058-6.

Jerden, James, Meteb Mejbel, Antonio Nilson Zamuner Filho, Monica Carroll, and Joanna Campe. 2024. “The Impact of Geochemical and Life-Cycle Variables on Carbon Dioxide Removal by Enhanced Rock Weathering: Development and Application of the Stella ERW Model.” *APPLIED GEOCHEMISTRY* 167 (June):106002. https://doi.org/10.1016/j.apgeochem.2024.106002.

Kantzas, Euripides P., Maria Val Martin, Mark R. Lomas, Rafael M. Eufrasio, Phil Renforth, Amy L. Lewis, Lyla L. Taylor, et al. 2022. “Substantial Carbon Drawdown Potential from Enhanced Rock Weathering in the United Kingdom.” *Nature Geoscience* 15 (5): 382–89. https://doi.org/10.1038/s41561-022-00925-2.

Kelland, Mike E., Peter W. Wade, Amy L. Lewis, Lyla L. Taylor, Binoy Sarkar, M. Grace Andrews, Mark R. Lomas, et al. 2020. “Increased Yield and CO_2 Sequestration Potential with the C_4 Cereal *Sorghum Bicolor* Cultivated in Basaltic Rock Dust-Amended Agricultural Soil.” *GLOBAL CHANGE BIOLOGY* 26 (6): 3658–76. https://doi.org/10.1111/gcb.15089.

Lamb, Anthony, Rhys Green, Ian Bateman, Mark Broadmeadow, Toby Bruce, Jennifer Burney, Pete Carey, et al. 2016. “The Potential for Land Sparing to Offset Greenhouse Gas Emissions from Agriculture.” *Nature Climate Change* 6 (5): 488–92. https://doi.org/10.1038/nclimate2910.

Larkin, Christina S., M. Grace Andrews, Christopher R. Pearce, Kok L. Yeong, David J. Beerling, Joshua Bellamy, Suzan Benedick, et al. 2022. “Quantification of CO2 Removal in a Large-Scale Enhanced Weathering Field Trial on an Oil Palm Plantation in Sabah, Malaysia.” *Frontiers in Climate* 4 (August). https://doi.org/10.3389/fclim.2022.959229.

Lefebvre, David, Pietro Goglio, Adrian Williams, David A.C. Manning, Antonio Carlos De Azevedo, Magda Bergmann, Jeroen Meersmans, and Pete Smith. 2019. “Assessing the Potential of Soil Carbonation and Enhanced Weathering through Life Cycle Assessment: A Case Study for Sao Paulo State, Brazil.” *Journal of Cleaner Production* 233 (October):468–81. https://doi.org/10.1016/j.jclepro.2019.06.099.

Mersi, Wilfried Von, Regina Kuhnert-Finkernagel, and Franz Schinner. n.d. “The Influence of Rock Powders on Microbial Activity of Three Forest Soils.” Accessed July 8, 2024. https://doi.org/10.1002/jpln.19921550107.

Olsson-Francis, K., A. E. Simpson, D. Wolff-Boenisch, and C. S. Cockell. 2012. “The Effect of Rock Composition on Cyanobacterial Weathering of Crystalline Basalt and Rhyolite.” *Geobiology* 10 (5): 434–44. https://doi.org/10.1111/j.1472-4669.2012.00333.x.

Pas, Emily E. E. M. te, Mathilde Hagens, and Rob N. J. Comans. 2023. “Assessment of the Enhanced Weathering Potential of Different Silicate Minerals to Improve Soil Quality and Sequester CO_2.” *FRONTIERS IN CLIMATE* 4 (January):954064. https://doi.org/10.3389/fclim.2022.954064.

Petavratzi, E., S. Kingman, and I. Lowndes. 2005. “Particulates from Mining Operations: A Review of Sources, Effects and Regulations.” *MINERALS ENGINEERING* 18 (12): 1183–99. https://doi.org/10.1016/j.mineng.2005.06.017.

Pogge Von Strandmann, Philip A. E., Chloe Tooley, Josephina J. P. A. Mulders, and Phil Renforth. 2022. “The Dissolution of Olivine Added to Soil at 4°C: Implications for Enhanced Weathering in Cold Regions.” *Frontiers in Climate* 4 (February):827698. https://doi.org/10.3389/fclim.2022.827698.

Reershemius, Tom, Mike E. Kelland, Jacob S. Jordan, Isabelle R. Davis, Rocco D’Ascanio, Boriana Kalderon-Asael, Dan Asael, et al. 2023. “Initial Validation of a Soil-Based Mass-Balance Approach for Empirical Monitoring of Enhanced Rock Weathering Rates.” *ENVIRONMENTAL SCIENCE & TECHNOLOGY* 57 (48): 19497–507. https://doi.org/10.1021/acs.est.3c03609.

Reis, Betania Roqueto, Ana Luisa Soares Vasconcelos, Antonio Marcos Miranda Silva, Fernando Dini Andreote, and Antonio Carlos Azevedo. 2024. “Changes in Soil Bacterial Community Structure in a Short-Term Trial with Different Silicate Rock Powders.” *CHEMICAL AND BIOLOGICAL TECHNOLOGIES IN AGRICULTURE* 11 (1): 61. https://doi.org/10.1186/s40538-024-00586-w.

Renforth, Phil, and Gideon Henderson. 2017. “Assessing Ocean Alkalinity for Carbon Sequestration.” *REVIEWS OF GEOPHYSICS* 55 (3): 636–74. https://doi.org/10.1002/2016RG000533.

Rigopoulos, Ioannis, Anna L. Harrison, Andreas Delimitis, Ioannis Ioannou, Angelos M. Efstathiou, Theodora Kyratsi, and Eric H. Oelkers. 2018. “Carbon Sequestration via Enhanced Weathering of Peridotites and Basalts in Seawater.” *Applied Geochemistry* 91 (April):197–207. https://doi.org/10.1016/j.apgeochem.2017.11.001.

Rijnders, Jet, Sara Vicca, Eric Struyf, Thorben Amann, Jens Hartmann, Patrick Meire, Ivan Janssens, and Jonas Schoelynck. 2023. “The Effects of Dunite Fertilization on Growth and Elemental Composition of Barley and Wheat Differ with Dunite Grain Size and Rainfall Regimes.” *FRONTIERS IN ENVIRONMENTAL SCIENCE* 11 (August):1172621. https://doi.org/10.3389/fenvs.2023.1172621.

Ryan, P. C., A. Santis, E. Vanderkloot, M. Bhatti, S. Caddle, M. Ellis, A. Grimes, et al. 2024. “The Potential for Carbon Dioxide Removal by Enhanced Rock Weathering in the Tropics: An Evaluation of Costa Rica.” *Science of The Total Environment* 927 (June):172053. https://doi.org/10.1016/j.scitotenv.2024.172053.

Schopka, H.H., L.A. Derry, and C.A. Arcilla. 2011. “Chemical Weathering, River Geochemistry and Atmospheric Carbon Fluxes from Volcanic and Ultramafic Regions on Luzon Island, the Philippines.” *Geochimica et Cosmochimica Acta* 75 (4): 978–1002. https://doi.org/10.1016/j.gca.2010.11.014.

Siebert, Stefan, and Petra Doell. 2010. “Quantifying Blue and Green Virtual Water Contents in Global Crop Production as Well as Potential Production Losses without Irrigation.” *JOURNAL OF HYDROLOGY* 384 (3–4): 198–217. https://doi.org/10.1016/j.jhydrol.2009.07.031.

Smith, Pete, Steven J. Davis, Felix Creutzig, Sabine Fuss, Jan Minx, Benoit Gabrielle, Etsushi Kato, et al. 2016. “Biophysical and Economic Limits to Negative CO2 Emissions.” *Nature Climate Change* 6 (1): 42–50. https://doi.org/10.1038/nclimate2870.

Strefler, Jessica, Thorben Amann, Nico Bauer, Elmar Kriegler, and Jens Hartmann. 2018. “Potential and Costs of Carbon Dioxide Removal by Enhanced Weathering of Rocks.” *ENVIRONMENTAL RESEARCH LETTERS* 13 (3): 034010. https://doi.org/10.1088/1748-9326/aaa9c4.

Stubbs, Amanda R., Ian M. Power, Carlos Paulo, Baolin Wang, Nina Zeyen, Sasha Wilson, Evelyn Mervine, and Chris Gunning. 2023. “Impact of Wet-Dry Cycles on Enhanced Rock Weathering of Brucite, Wollastonite, Serpentinite and Kimberlite: Implications for Carbon Verification.” *CHEMICAL GEOLOGY* 637 (October):121674. https://doi.org/10.1016/j.chemgeo.2023.121674.

Suchet, P. A., J. L. Probst, and W. Ludwig. 2003. “Worldwide Distribution of Continental Rock Lithology:: Implications for the Atmospheric/Soil CO_2 Uptake by Continental Weathering and Alkalinity River Transport to the Oceans -: Art. No. 1038.” *GLOBAL BIOGEOCHEMICAL CYCLES* 17 (2): 1038. https://doi.org/10.1029/2002GB001891.

Swoboda, Philipp, Thomas F. Döring, and Martin Hamer. 2022. “Remineralizing Soils? The Agricultural Usage of Silicate Rock Powders: A Review.” *Science of The Total Environment* 807 (February):150976. https://doi.org/10.1016/j.scitotenv.2021.150976.

Taylor, Lyla L., Charles T. Driscoll, Peter M. Groffman, Greg H. Rau, Joel D. Blum, and David J. Beerling. 2021. “Increased Carbon Capture by a Silicate-Treated Forested Watershed Affected by Acid Deposition.” *Biogeosciences* 18 (1): 169–88. https://doi.org/10.5194/bg-18-169-2021.

“The Paris Agreement | UNFCCC.” n.d. Accessed July 25, 2024. https://unfccc.int/process-and-meetings/the-paris-agreement.

Vanderkloot, Elizabeth, and Peter Ryan. 2023. “Quantifying the Effect of Grain Size on Weathering of Basaltic Powders: Implications for Negative Emission Technologies via Soil Carbon Sequestration.” *Applied Geochemistry* 155 (August):105728. https://doi.org/10.1016/j.apgeochem.2023.105728.

Vicca, Sara, Daniel S. Goll, Mathilde Hagens, Jens Hartmann, Ivan A. Janssens, Anna Neubeck, Josep Penuelas, et al. 2022. “Is the Climate Change Mitigation Effect of Enhanced Silicate Weathering Governed by Biological Processes?” *GLOBAL CHANGE BIOLOGY* 28 (3): 711–26. https://doi.org/10.1111/gcb.15993.

Vienne, Arthur, Silvia Poblador, Miguel Portillo-Estrada, Jens Hartmann, Samuel Ijiehon, Peter Wade, and Sara Vicca. 2022. “Enhanced Weathering Using Basalt Rock Powder: Carbon Sequestration, Co-

Benefits and Risks in a Mesocosm Study With *Solanum Tuberosum*." *FRONTIERS IN CLIMATE* 4 (May):869456. https://doi.org/10.3389/fclim.2022.869456.

Weber, Sebastian, and Raul E. Martinez. 2017. "Effects of *Synechococcus* Sp Cyanobacteria Inert Biomass on Olivine Dissolution: Implications for the Application of Enhanced Weathering Methods." *APPLIED GEOCHEMISTRY* 84 (September):162–72. https://doi.org/10.1016/j.apgeochem.2017.06.011.

White, Art F, and Susan L Brantley. 2003. "The Effect of Time on the Weathering of Silicate Minerals: Why Do Weathering Rates Differ in the Laboratory and Field?" *Chemical Geology* 202 (3–4): 479–506. https://doi.org/10.1016/j.chemgeo.2003.03.001.

Yan, Yongxue, Xiaohan Dong, Renshan Li, Yankuan Zhang, Shaokui Yan, Xin Guan, Qingpeng Yang, et al. 2023. "Wollastonite Addition Stimulates Soil Organic Carbon Mineralization: Evidences from 12 Land-Use Types in Subtropical China." *CATENA* 225 (May):107031. https://doi.org/10.1016/j.catena.2023.107031.

Yu, Dong, Jiayi Deng, Qing Jiang, Hanshuang Liu, Chenglong Yu, Hui Ma, and Shengyan Pu. 2024. "Evaluation of Groundwater Quality with Multi-Source Pollution Based on Source Identification and Health Risks." *SCIENCE OF THE TOTAL ENVIRONMENT* 949 (November):175064. https://doi.org/10.1016/j.scitotenv.2024.175064.

Zhou, Qiyu. 2024. "Potential CO_2 Capture via Enhanced Weathering by Basaltic Sand Spreading on Golf Courses in the US." *INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL* 131 (January):104032. https://doi.org/10.1016/j.ijggc.2023.104032.