

Review

Exploratory Review on Environmental Aspects of Enhanced Weathering as a Carbon Dioxide Removal Method

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Abstract: The accumulation of carbon dioxide in the atmosphere due to fossil fuel burning and deforestation has caused global warming and an increase in extreme weather events. To complement the shift towards clean energy, it is crucial to adopt methods for carbon dioxide removal, known as negative emission technologies. Enhanced weathering is one such approach that involves accelerating the natural process of rock weathering by spreading finely ground rocks over large areas, such as agricultural land or coastal areas. This exploratory review paper provides an overview of the fundamental mechanisms behind enhanced weathering, and outlines the techniques for its implementation. The environmental benefits of enhanced weathering are highlighted, including carbon dioxide removal, and improvement of soil fertility. Furthermore, potential impacts on ecosystems and biodiversity are examined, along with the effects on water, soil and air quality. The paper also considers the risks and challenges associated with large-scale implementation and long-term stability of enhanced weathering. Additionally, the integration of enhanced weathering with Sustainable Development Goals is explored, along with the potential co-benefits and trade-offs with other sustainability objectives. To conclude, this exploratory review paper summarizes the key findings and proposes avenues for further research in this field of enhanced weathering.

Keywords: negative emission technology; soil amendment; basalt; olivine



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1. Introduction

Global warming is one of the greatest challenges to humankind today, manifesting in increased occurrences in extreme weather events such as heat waves, cold spells, storms, floods, and droughts. The consequences of global warming extend to rising sea levels, coastal flooding, saltwater intrusion into freshwater sources, ocean acidification, ecosystem disruptions, and threats to food and water security, as well as human health [1]. Carbon dioxide (CO₂) is the primary greenhouse gas responsible for climate change, with atmospheric concentrations having risen by 50% compared to pre-industrial levels due to human activities, notably fossil fuel burning and deforestation. While efforts are underway to reduce greenhouse gas emissions by transitioning to renewable energy sources, such as wind and solar power, these actions alone are not sufficiently rapid to achieve the targets set by the Paris Agreement, which aims to limit global warming to below 2 °C, preferably 1.5 °C, above pre-industrial levels [2]. Hence, the development of carbon dioxide removal (CDR) methods, also known as negative emission technologies (NET), is imperative. These technologies enable the removal of current and previously accumulated CO₂ emissions and help compensate for emissions from sectors that are difficult to decarbonize, thus facilitating the achievement of net-zero emissions. CDR technologies encompass various approaches, including afforestation, bioenergy with carbon capture and storage (BECCS), biochar soil amendment, direct air capture (DAC), enhanced rock weathering (EW), and ocean fertilization.

Enhanced weathering with olivine was identified as a particularly promising NET, besides forestation, soil carbon sequestration and direct air carbon capture and storage, based on a topical review evaluating 36 NETs and practices [3]. The latter authors indicate overall good performance and considerable co-benefits for EW. Also, earlier studies identified the geoengineering potential of EW as an effective and cheap way to sequester CO₂ [4,5]. Moreover, EW was determined to be competitive with other large-scale CDR technologies in terms of energy and water demands [6]. However, another study applied an integrated model of fuzzy analytical hierarchy process and interval-extended Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) on seven NETs and identified bioenergy with carbon capture and storage as the most promising NET, and EW ranked last due to the relatively high energy requirement, low capture capacity and technology immaturity [7]. One of the key advantages of EW is its relatively low land use and minimal reliance on water resources compared to other CDR technologies [8]. Unlike bio-based NETs, EW can sequester CO₂ without compromising food production. Moreover, it is cost-competitive in comparison to other CDR technologies, with estimates suggesting affordable prices of 63 US \$ per ton CO₂ for dunite (mainly composed of olivine) and 81 to 211 US \$ per ton CO₂ for basalt enhanced weathering [9,10]. Coastal EW, as demonstrated by project Vesta, is estimated at a cost-effective range of 34 to 50 \$ per ton at the 1–10 Mt scale [3]. The use of alkaline waste as an alternative feedstock for EW could further reduce costs [11,12]. These cost-effective characteristics make EW an appealing option among CDR technologies. Note that cost plays a huge role, given the magnitude, in the order of tens of gigatonnes, of CO₂ that needs to be removed from the atmosphere per year in order to make a difference in mitigating climate change. Furthermore, advancements in electrochemically mediated EW processes, such as integrated water electrolysis and mineral weathering, show promise, although total costs are highly dependent on the energy source utilized, with potential costs reaching 614 \$ per ton CO₂ [13]. The type of energy source used in EW also influences the environmental impact, as documented in life cycle assessment studies of CDR technologies [14].

This paper focuses on EW as a method to remove CO₂ from the atmosphere by accelerating the natural process of rock weathering. EW utilizes chemical reactions between rocks, particularly mafic and ultramafic rocks, water and CO₂ to sequester atmospheric CO₂ more rapidly than occurs naturally [15,16]. It is a viable CDR technology that involves grinding suitable rocks to increase the mineral dissolution rates and spreading them over extensive areas, such as agricultural land or coastal regions. Warm and humid regions are particularly favorable for EW [10]. Coastal EW involves the dispersion of minerals on beaches that are then further transferred to the ocean by wave action [17]. In addition to CDR, terrestrial EW applied to agricultural land can enhance crop growth and soil fertility, potentially serving as a partial substitute for conventional fertilizers and mitigating the environmental impacts of agriculture [15]. Moreover, EW can be synergistically combined with other CDR technologies like BECCS and biochar, thereby enhancing their feasibility and carbon sequestration potential [9,18].

Despite the immense promise of EW, researchers emphasize the importance of further investigation of the risks associated with EW, particularly related to human health [3]. Implementation of EW requires large-scale mining, grinding, and spreading operations, which involve dust generation that can cause health risks to workers [19]. Mining activities may also damage ecosystems. Still, the activities are subject to environmental regulations [20], and strict adherence to these regulations and sustainable practices may facilitate social acceptance and long-term effectiveness of EW as CDR technology. Furthermore, instead of mining virgin material, utilizing mining waste could be preferable [20], if this waste does not result in leaching of toxic elements. However, this approach of using waste material may reduce earlier estimates of the sequestration potential of up to 21.3 Gt CO₂ per year through EW of basalt [21].

Our goal with this exploratory review is to provide the readers with a general understanding of enhanced weathering, emphasize its environmental aspects, and stimulate

further research in this field. The environmental aspects are important because the deployment of EW could affect ecosystems, biodiversity, and water and air quality, which will need to be thoroughly assessed and requires future investigation.

2. Methodology for this Review

For the selection of papers to be included in this review, we have searched using relevant keywords, such as enhanced weathering. We focused thereby on papers from mainly the last five years. Notably, we took account of the quality of the papers by searching mainly in high quality scientific journals (mainly Q1 journals), publications from established academics in the field (research groups who have a track record of Q1 journal publications in this field), and considered how many times the paper had been cited. Besides a background study of the literature, we analyzed the content and reference, and present the key findings, as well as our own evaluation and future perspectives. We aimed to cover the broad range of environmental aspects of enhanced weathering (i.e., air, water, soil, ecosystems, biodiversity), and thus, give a broad overview of all environmental considerations related to enhanced weathering, rather than selecting one very narrow focus. We took this approach because of the highly interdisciplinary nature of the topic, and to provide a comprehensive document for anyone who wants to gain a quick insight into the several benefits and potential concerns of enhanced weathering technology.

3. Enhanced Weathering

The process of enhanced weathering to remove CO₂ from the atmosphere involves several steps, including the selection of appropriate rocks, grinding of rocks to increase surface area, spreading of the ground rocks, mineral weathering, pH effect, carbonate precipitation, alkalinity, and feedback loops.

3.1. Rock Type

The selection of suitable rocks for EW is crucial. Rocks with high reactivity are preferred, since mineral dissolution is the rate-limiting step in mineral carbonation [22]. Ultramafic rocks, such as dunite and peridotite, are well-suited for this purpose. These igneous rocks have a low silica content (less than 45%) and generally high levels of MgO and FeO. They contain significant amounts of olivine [(Mg,Fe)₂SiO₄] and pyroxene [Ca_x(Mg,Fe)_{2-x}Si₂O₆] minerals, which react rapidly. Table 1 presents dissolution rate constants for several silicate minerals [23]. Additionally, some naturally altered ultramafic rocks may contain brucite and serpentine, which are highly reactive. Brucite reacts more rapidly than serpentine minerals such as chrysotile [24]. Wollastonite [CaSiO₃] exhibits a higher reaction rate than olivine and pyroxene, but its occurrence is more limited [25]. The leachability of Mg from ultramafic rocks may also be influenced by the presence of certain elements in the minerals. For instance, iron (Fe) can lead to surface passivation by ferric precipitates, reducing the efficiency of carbon sequestration [26–28]. Moreover, most silicate minerals dissolve incongruently, meaning that dissolution does not occur in molar ratios according to their composition, but rather the more soluble components are preferentially released. Mafic rocks, including coarse-grained gabbro and fine-grained basalt, have lower reactivity compared to peridotite [29], but they can be useful as additives for agricultural soils in EW [15]. Additionally, basaltic amorphous glass exhibits higher reactivity than crystalline olivine [30]. Certain industrial waste materials that may not be fully crystalline could also react rapidly, although they may have relatively low concentrations of calcium (Ca) and magnesium (Mg), making them less efficient for permanent CO₂ storage [12]. Various types of alkaline waste, including iron and steel slag, demolition waste, and mine tailings from nickel, chrysotile, kimberlite, and red mud mining, have been studied for passive carbonation [31].

Table 1. Silicate mineral dissolution rate constants (in mol m⁻² s⁻¹) at 25 °C, pH 0 [32]. Table adapted from Manning and Theodoro [23].

| Mineral Family | Mineral | Formula | Release | Typical Content (wt%) | Dissolution Rate Constant |
|----------------|--------------|--|---------|-----------------------|---------------------------|
| Feldspatoid | Nepheline | (Na,K)AlSiO ₄ | K | 4.2 | -2.73 |
| Plagioclase | Anorthite | CaAl ₂ Si ₂ O ₈ | Ca | 13.6 | -3.50 |
| Mica | Glauconite | K(Fe ³⁺ ,Al,Mg) ₂ (Si,Al) ₄ O ₁₀ (OH) ₂ | K, Mg | 7.5, 3.0 | -4.80 |
| Pyroxene | Wollastonite | CaSiO ₃ | Ca | 33.6 | -5.37 |
| Feldspatoid | Leucite | KAlSi ₂ O ₆ | K | 17.4 | -6.00 |
| Pyroxene | Diopside | CaMgSi ₂ O ₆ | Ca, Mg | 18.6 | -6.36 |
| Tourmaline | Dravite | NaMg ₃ Al ₆ B ₃ Si ₆ O ₃₀ (OH) | Mg, B | 7.8, 3.5 | -6.50 |
| Olivine | Forsterite | Mg ₂ SiO ₄ | Mg | 33.6 | -6.85 |
| Amphibole | Hornblende | Ca ₂ (Mg,Fe) ₄ Al[Si ₂ AlO ₂₂](OH) ₂ | Ca, Mg | 8.6, 7.8 | -7.00 |
| Pyroxene | Enstatite | Mg ₂ Si ₂ O ₆ | Mg | 35.0 | -9.02 |
| Mica | Biotite | K(Fe,Mg) ₃ AlSi ₃ O ₁₀ (OH) ₂ | K, Mg | 7.5, 3.6 | -9.84 |
| K-feldspar | Orthoclase | KAlSi ₃ O ₈ | K | 14.1 | -10.06 |
| Plagioclase | Albite | NaAlSi ₃ O ₈ | Na | 8.7 | -10.16 |
| Mica | Muscovite | KAl ₃ Si ₃ O ₁₀ (OH) ₂ | K | 9.1 | -11.85 |

3.2. Particle Size, Shape and Reactive Surface Area

In addition to the rock type, also particle size and surface area play a crucial role in the efficiency of CDR through EW. Smaller particles have a higher surface area to volume ratio than larger particles, making them more favorable for EW as they provide a larger reactive surface area, leading to higher reaction rates per unit volume or weight of source material. Several studies have reported a higher carbonation rate in finer particle size distributions [24,33–35]. Glacial rock flour is a finely grained material, and a study on the application of 50 tons ha⁻¹ of Greenlandic (biotite-rich) glacial rock flour on an acidic, sandy soil in Denmark led to an estimated CO₂ uptake of 728 kg ha⁻¹ over a period of 3 years [36]. The shape of the mineral may also impact the reaction rate. For instance, fibrous serpentine, with its high surface area to volume ratio, can react rapidly [25]. Furthermore, the platy structure of biotite promotes faster EW compared to the three-dimensional framework structure of microcline and nepheline [37]. It is important to note that mineral dissolution is influenced by crystal defects and imperfections, making the relationship between mineral dissolution and mineral specific surface area more complex. Therefore, the mineral reactive surface area may differ from the mineral specific surface area [38].

Grinding the rocks will produce a certain particle size distribution with smaller particles, which will vary depending on the mechanical properties and the original particle size distribution of the source material. However, grinding requires energy, and although it reduces particle size and increases reaction rates, the energy cost of EW increases (Figure 1), impacting the overall efficiency of CDR beyond the EW mineral reaction rate [10]. Nonetheless, it is estimated that a slight increase in grinding cost to achieve particle surface areas of 10–100 m²/g using 100–500 kWh/t could significantly enhance the rate of carbon mineralization through EW [25].

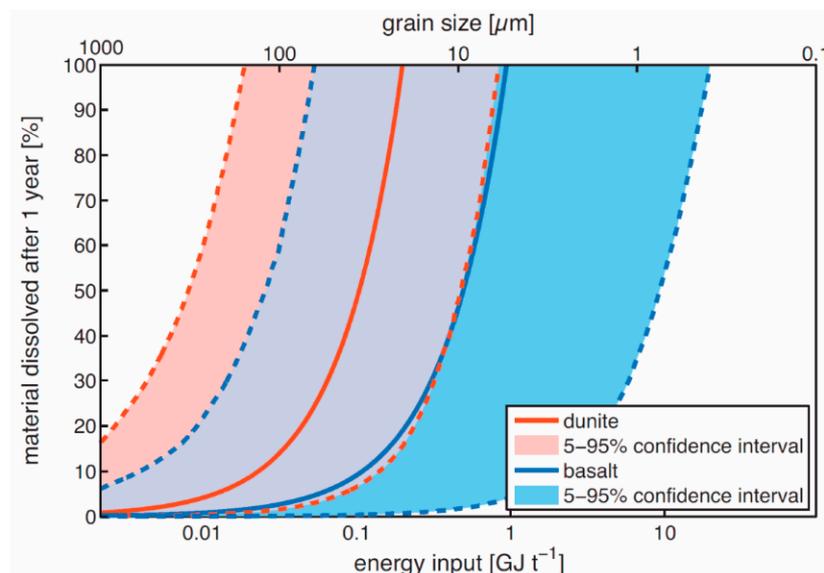


Figure 1. Percentage of dissolved mineral after 1 year against mineral grain size and required energy for grinding. Figure from Strefler et al. [10], reproduced with permission from IOP Science.

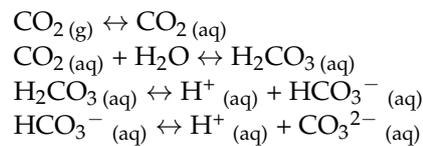
3.3. Spreading Ground Rock

Ground ultramafic and mafic rocks can be spread on agricultural soil, forest soil, or beaches as a method to remove CO₂ from the air. Enhanced weathering has been suggested for a wide variety of land systems, despite the very different soil composition, texture, hydrology and pH [4,15,39]. The effects of soil type as well as precipitation seasonality, irrigation and vegetation cycle have been explored through modeling of case studies across different sites [40]. Nevertheless, the efficiency of EW in different soil types requires further exploration. In most experimental studies, olivine mineral, dunite or basalt rock was used [41–47]. There are fewer studies on wollastonite [48], fibrous serpentine known as chrysotile [49], and brucite [50] due to their lower abundance. The spreading of ground rock on soil increases the rate of mineral dissolution because microbial processes in the soil enhance the efficiency of EW [51]. Microbial degradation of organic matter in the soil generates chelating agents, organic acids, and inorganic acids that contribute to the acceleration of mineral dissolution [25]. Soil pH plays a crucial role in mineral dissolution rates and nutrient release in the soil [52]. Therefore, the addition of mineral weathering bacteria that produce siderophores, organic acids, sulfuric acid, or nitric acid, or induce redox reactions, can further enhance the release of nutrients through faster mineral dissolution [53]. The presence of sulfides in the soil can enhance Mg leaching due to the activity of acid-generating microbes [54,55]. Additionally, the uptake of atmospheric CO₂ in water can be accelerated by carbonic anhydrase [56]. Furthermore, microbial processes can increase the local partial CO₂ pressure by 10 to 100 times the atmospheric concentration [54], thus promoting acidity and enhancing mineral dissolution [57]. Upon acid leaching of ultramafic mine tailings, the presence of cyanobacteria can then enable the precipitation of magnesium carbonate minerals from those fluids [58–60].

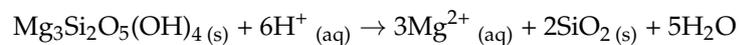
3.4. Mineral Dissolution and Carbon Storage

Several chemical reactions are involved in the process of EW for carbon storage. First, atmospheric CO₂ gas dissolves in water, and forms carbonic acid. Bicarbonate and carbonate ions become available in the solution, the extent of which depends also on the pH of the water. The reaction kinetics are also important. Dissolution of CO₂ in water to form carbonic acid is generally slow, whereas the conversion between carbonic acid and bicarbonate ions is fast. The enzyme carbonic anhydrase is known to catalyze the

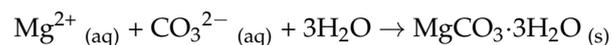
conversion between CO₂ and water and the carbonic acid dissociated ions. The following chemical reactions are at play:



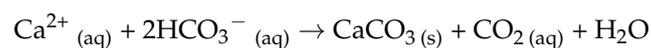
Second, the formation of carbonic acid aids in the dissolution of (ultra)mafic rocks and minerals, such as olivine, and leads to the release of cations. The dissolution of these rocks and minerals will cause an increase in pH of the water, and thus, a larger availability of bicarbonate and, in particular, carbonate ions. In this way, carbon is removed from the atmosphere and trapped as bicarbonate and carbonate ions in water. Through runoff, these ions can eventually be transported to the oceans, where their residence time can exceed 100,000 years [3]. As an example, following the dissolution of CO₂ in water, resulting in a pH decrease, serpentine may dissolve and create a more alkaline environment.



Third, the creation of a more alkaline environment can then lead to the precipitation of nesquehonite, for example, as follows:



Thus, depending on soil conditions, some cations can bind with carbonate ions to form carbonate minerals. As the source rocks and minerals (e.g., olivine) dissolve, the pH in the water increases, and the alkalinity of the water increase, favouring subsequent precipitation of carbonates. It should be noted that part of the CO₂ sequestered through uptake in water may be released again during carbonate mineral formation or through reactions with acidic species [9,61]. This is illustrated by the overall reaction of anorthite, with dissolution of 1 mol anorthite delivering 2 mol bicarbonate ions, and subsequent precipitation of calcite leading to release of 1 mol CO₂ again.



The type of carbonate formed depends on the type and concentration of cations released from mineral dissolution, as well as temperature, pH and composition of the water. The most common carbonates formed with Ca or Mg ions in solution include calcite [CaCO₃], magnesite [MgCO₃] and dolomite [CaMg(CO₃)₂], or hydrated forms like hydromagnesite [Mg₅(CO₃)₄(OH)₂·4H₂O], dypingite [Mg₅(CO₃)₄(OH)₂·xH₂O], lansfordite [MgCO₃·5H₂O], nesquehonite [MgCO₃·3H₂O], hydrotalcite [Mg₆Al₂CO₃(OH)₁₆·4H₂O], and others. Some naturally altered ultramafic rocks may contain brucite [Mg(OH)₂], serpentine [(Mg,Fe)₃Si₂O₅(OH)₄] and talc [Mg₃Si₄O₁₀(OH)₂], which can also react with CO₂ to form carbonates [25]. The reactions of dissolved CO₂ with wollastonite, olivine, brucite or serpentine, are all spontaneous and exothermic.

Carbon dioxide dissolution, mineral dissolution and carbonate precipitation are influenced by climatic factors. Lower temperatures favour more CO₂ dissolution in water based on Henry's law, but higher ambient temperatures accelerate the dissolution of Mg-containing minerals and CO₂ sequestration. For example, a tenfold increase in carbon storage has been observed with a temperature increase from 10 to 40 °C [62]. Experiments on olivine dissolution in soil show that the dissolution rate is two orders of magnitude lower at 4 °C compared to 19 °C, as shown in Figure 2 [63]. The ambient temperature and the temperature difference between the ambient temperature and the soil temperature affect CO₂ ingress into the soil, with higher ambient temperatures favoring CO₂ penetration [64].

The permeability of the soil also affects the circulation of CO_2 , and the ingress of CO_2 is a primary control on acidification, which in turn results in the leaching of Mg from the source material required for subsequent carbonation [65,66]. The water content in the soil also plays a crucial role in carbonation. Carbon mineralization increases with higher water frequency and lower saturation [26]. The latter stimulates oversaturation of Mg carbonate and increases pH, favoring carbonate formation. Additionally, freeze/thaw and wetting/drying cycles have been observed to enhance carbonation [33,67]. Evaporation also contributes to a higher carbonation rate, which is attributed to the higher salinity of the water and capillary action of water causing upward flow to the dry surface exposed to sunlight and dry air circulation [55,68].

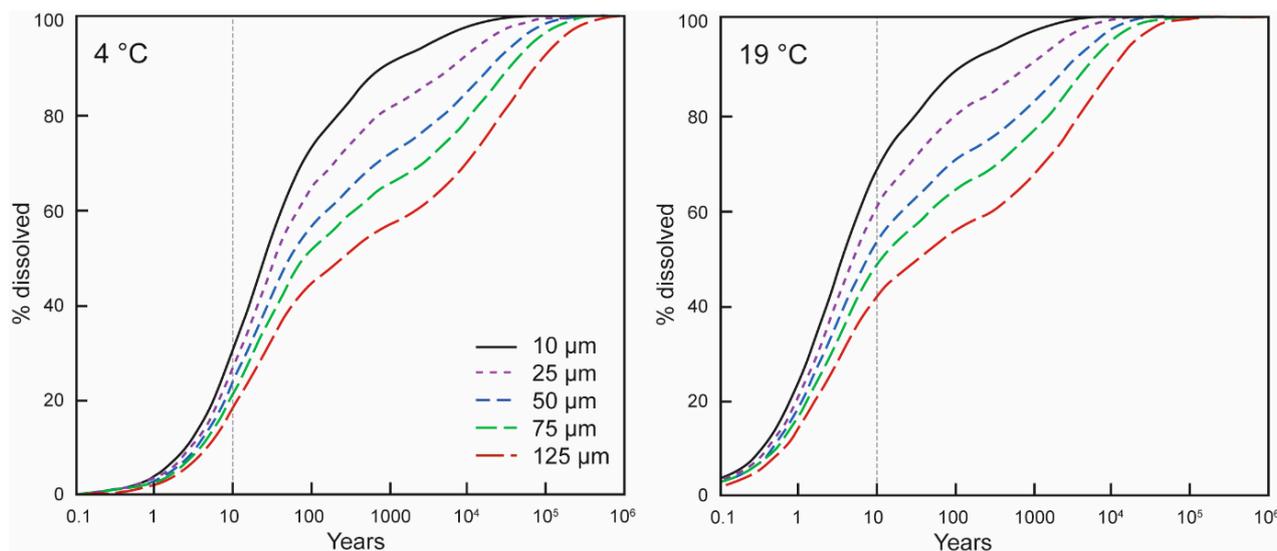


Figure 2. Modeled dissolution percentage against time for olivine of different grain sizes based on a shrinking core model at a temperature of 4 °C (left panel) and of 19 °C (right panel). The vertical dashed lines represent dissolution percentages after 10 years. Figure adapted from Pogge von Strandmann et al. [63].

3.5. Acidity

Different environments can have varying pH levels. Soils can be either acidic or alkaline depending on soil mineralogy, climatic factors, plant and microbial communities. Moreover, soils can contain strong acids, such as nitric acid resulting from excessive use of nitrogenous fertilizers, or sulfuric acid caused by acid rain affected by sulfur oxide emissions. The rate of mineral dissolution is pH-dependent and varies among different minerals. Some minerals dissolve more rapidly in acidic environments, whereas others have a favorable dissolution rate in higher pH environments. For instance, aluminum-free minerals like olivine and pyroxene generally dissolve faster in acidic, low pH, whereas aluminum-bearing minerals like plagioclase and volcanic glass have dissolution rates that increase with higher pH [22]. Therefore, olivine and pyroxene minerals may be preferable for terrestrial EW in acidic soils, whereas coastal EW with slightly alkaline water may benefit from other mineral choices. Moreover, the presence of iron in ultramafic rocks can trigger iron oxidation due to dissolved oxygen in rainwater, leading to a decrease in pH. However, dissolved iron can result in the formation of iron hydroxides at higher pH levels, which may inhibit the dissolution of magnesium-containing minerals, thus negatively affecting carbon storage [62]. One potential strategy to prevent inhibition of Mg leaching and to regulate pH within the alkaline range is the use of CDTA chelating agents [26].

3.6. Feedback Loops

Feedback loops can either amplify or diminish the effects of EW, thereby influencing the overall efficiency and sustainability of EW as a CDR strategy. EW releases nutrients

such as magnesium, calcium and iron, which promote better crop growth. This initiates a positive feedback loop, as improved plant growth leads to increased photosynthesis and carbon uptake, thereby amplifying the efficiency of CDR. Additionally, enhanced plant growth results in more plant material that eventually decomposes, releasing organic matter and nutrients back into the soil. This stimulates microbial activity and nutrient cycling, enriching the soil. Furthermore, biological activity can enhance the dissolution rate of applied minerals. This positive feedback loop improves soil fertility and enhances the effectiveness of EW on agricultural land. Moreover, the application of silicate minerals through EW provides silicon (Si) to the soil. The supply of Si in the soil improves plant resilience to drought stress and enhances their resistance against diseases. Therefore, the release of Si through EW could lead to higher CDR due to improved plant growth in less favorable soil conditions [69].

Regarding mineral dissolution and carbonate precipitation reactions, a negative feedback loop can occur due to carbonate formation at reactive sites, hindering further CO₂ ingress for additional carbonation [70]. Similarly, the formation of passivation layers, such as silica gel polymerization, can inhibit the supply of CO₂ to reactive sites [26]. Furthermore, permeability in the soil or rock material can be a limiting factor, which depends on the relative dissolution rate versus carbonate formation rate [31]. Mineral dissolution and carbonate formation can also lead to a positive feedback loop in cases where carbonate formation causes volume expansion and the formation of cracks in the rock, known as reaction-driven cracking [71]. This opens up more pathways for CO₂ [25]. Feedback loops can have both positive and negative impacts on EW, and understanding and managing those feedback loops is crucial to optimize the long-term viability of EW as a CDR technology.

4. Techniques for Implementing Enhanced Weathering

4.1. Implementation Techniques

Various techniques have been explored and developed for implementing EW as a CDR strategy. These techniques aim to accelerate the natural process of rock weathering by increasing the contact between rocks and carbon dioxide dissolved in water.

One technique involves grinding olivine minerals or basaltic rocks, which are then spread over larger land areas such as agricultural fields, degraded land, or forest areas [46]. Depending on the scale, the rock powder can be spread manually or using equipment that is commonly employed for fertilizer spreading on the ground, or through the use of helicopters or fixed-wing aircraft equipped with agricultural spreaders [45]. The rock powder can be mixed with the soil on agricultural land to improve soil fertility through nutrient supply resulting from mineral dissolution during EW. In forest areas, the powder can be spread using helicopters, following similar methods used for liming forest soil to counteract soil acidity [72]. The small particles then come into contact with CO₂ dissolved in water, and over time, the minerals dissolve and, if the pH is sufficiently high, carbonate precipitation may occur, effectively sequestering the captured CO₂ for the long term.

In practice, the soil mineralogy needs to be considered in relation to the composition of the ground rock applied for EW, as a chemical non-equilibrium between the mineral and the soil water is necessary to achieve mineral dissolution [73]. Table 2 provides an overview of reported CO₂ removal rates from studies on EW with rock powder in soil. It is expected that EW may be limited if ground rock minerals are added to soil where those minerals are already present and have reached equilibrium with the soil [52]. Previous studies have demonstrated the positive impact of different mineralogy between soil and ground rock powder, as well as lower pH, on plant growth [74]. Additionally, the type of plant species in the soil influences the rate of EW and the type of element released. For example, plants like maize, which release phytosiderophores (strong iron chelants) contribute to favorable EW [38,75]. Bacteria and fungi also play a role in rock weathering [76]. Experiments with wollastonite have shown significantly higher weathering rates for minerals within a soil environment [77]. Climatic conditions, particularly temperature and rainfall, also impact

EW. Hydrolysis of silicate minerals is endothermic. Thus, higher temperatures accelerate mineral dissolution rates, aligning with faster EW in tropical climates. Furthermore, mineral dissolution is more efficient with higher rainfall, as water movement through the soil creates conditions where soil solutions are not in equilibrium with the minerals, favoring EW [38].

Table 2. Overview of CO₂ removal rates of enhanced weathering in soil studies, adapted from Wood et al. [77].

| Material | Scale | Plant Presence | Dosage (t/ha) | CO ₂ Capture Metric | Ton CO ₂ /ha/yr | Reference |
|--------------|-----------|----------------|---------------|---------------------------------------|----------------------------|-----------|
| Basalt | Mesocosm | Yes | 100 | Mg balance | 3.01 | [46] |
| Concrete | Field | No | Not stated | SIC | 85 | [78] |
| Dolerite | Field | Yes | Not stated | SIC | 17.6 | [79] |
| Olivine | Pot | Yes | 204 | Mg balance | 2.69 | [80] |
| Olivine | Mesocosm | Yes | 220 | Mg balance | 0.05 | [41] |
| Olivine | Column | No | 50 | Mg balance | 4.16 | [81] |
| Olivine | Column | No | 127 | Mg balance | 0.30 | [63] |
| Wollastonite | Pot | Yes | 221 | SIC | 39.3 | [82] |
| Wollastonite | Field | Yes | 1.25–5.0 | SIC | 0.28–2.4 | [83] |
| Wollastonite | Watershed | Yes | 3.44 | Ca balance | 0.77 | [48] |
| Wollastonite | Column | No | 221 | Si, Ca, HCO ₃ [−] | 24.5–52.9 | [77] |

In addition to spreading rock powder on agricultural, degraded or forest lands for terrestrial EW, silicate rock powder can also be distributed over coastal areas or added directly to the ocean [22]. However, the practical implementation using aircraft for material dispersion has been found to have some drawbacks, including the impacts of wind drift on powder discharge and spreading, as well as the associated CO₂ emissions contributing to the overall carbon footprint [84]. The latter study suggests that surface vessels are a more cost-effective option compared to aircraft [84]. In coastal areas, the action of waves and tidal currents can accelerate the weathering of rock particles, leading to an increase in seawater alkalinity and subsequent removal of atmospheric CO₂ [85]. The potential for large-scale CDR through addition of minerals in the ocean has been evaluated using biogeochemical models. The results indicate that natural materials such as olivine and basalt have low CDR efficiency while significantly impacting marine food quality and the production of fecal pellets by marine zooplankton, as illustrated in Figure 3 [86]. The latter study also suggests that synthetic metal oxide materials may have greater CDR potential with lower environmental impact, but their large-scale deployment presents challenges [86]. Tests involving the addition of olivine powder to seawater in a marine area have shown an impact on the microbial community, with a higher relative abundance of biofilm-forming microbes observed in the particle-attached fraction [87].

Mining waste can also be used for carbon mineralization as an approach for implementing terrestrial EW. The efficiency of EW using mine tailings depends on various factors. The composition of the mine waste is a crucial factor as the reactivity of different minerals varies. Moreover, the mines should have tailings of minerals that can release alkaline ions. Tailings with a high content of olivine, serpentine, and diopside are particularly suitable for CDR due to their high weathering rate [88]. It is also important to consider the potential presence of carbonate minerals, such as calcite in kimberlite rocks, as these can be easily leached but have a negative impact on CDR [89]. Climatic factors, including temperature, water content in the mine tailings, evaporation, and rainfall patterns, play significant roles in the efficiency of EW using mine waste [90]. The availability of CO₂ in the tailings is also crucial, as CO₂ dissolution in water contributes to mineral dissolution and the release of alkaline ions. Aeration of mine tailings by air sparging, as shown in Figure 4, can accelerate CO₂ sequestration by approximately five times [91]. Inverse geochemical modeling has indicated that the rate of passive carbonation of mine waste changes dynamically with mining and mine waste management practices [92]. Additionally, the presence and type

of biological species in the mine tailings can influence the rate of CO₂ uptake, mineral dissolution, and carbonate formation [90].

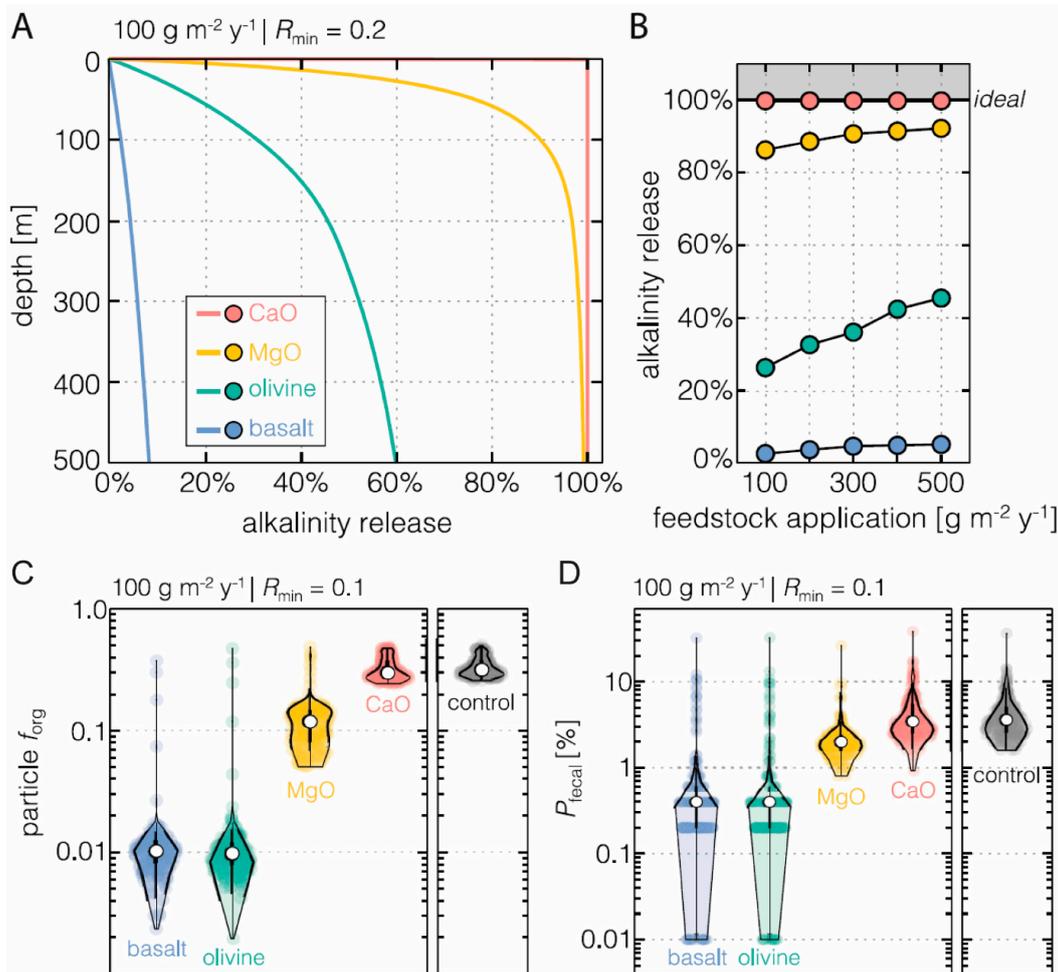


Figure 3. Solid feedstock alkalinity release and its impact on marine particle composition and zooplankton grazing in the particle model. (A) Depth versus relative alkalinity increase for natural basalt, olivine, MgO and CaO for an idealized coastal marine ecosystem with a feedstock application rate of 100 gC m⁻² yr⁻¹ and a ratio of feedstock application rate to net primary productivity of 0.2 (g/g). (B) Alkalinity release in the top 80 m of the water column against feedstock application rate. (C) Average particle matter fraction in the upper 200 m for different feedstocks, and the control without feedstock addition, for an idealized coastal marine ecosystem with a feedstock application rate of 100 gC m⁻² yr⁻¹ and a ratio of feedstock application rate to net primary productivity of 0.1 (g/g). (D) Production of zooplankton fecal pellets in the top 200 m for different feedstock application, and the control without feedstock addition. Figure from Fakhraee et al. [86], reprinted with permission from IOP Science.

In addition to naturally occurring rocks and mine waste, industrial waste such as metallurgical slag can be utilized as part of the EW strategy for CDR [93]. The potential of EW using industrial waste, including slag, combustion ash, cement kiln dust, red mud, construction waste, and mine tailings, is estimated to reach 2.9 to 8.5 Gt CO₂ per year by 2100 [12]. The large-scale implementation of EW using non-hazardous industrial waste can be facilitated through optimization models that allocate waste to specific application sites [94–96].

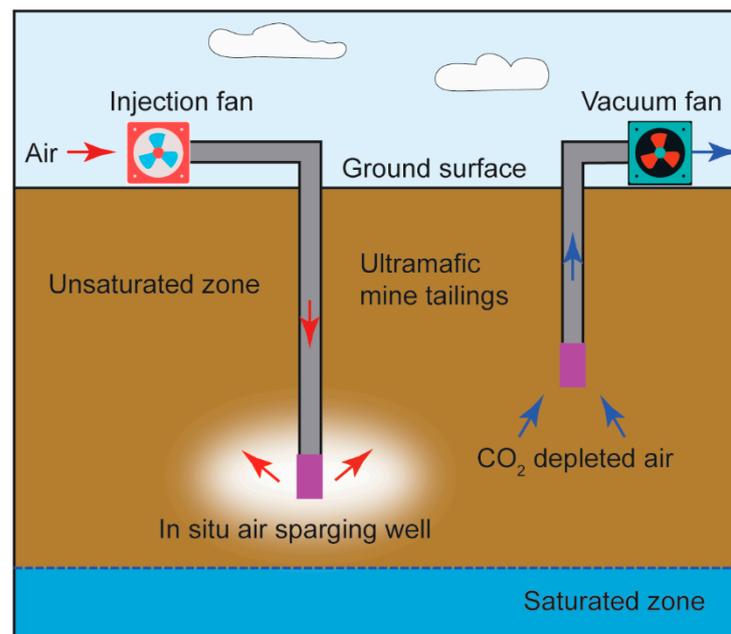


Figure 4. Conceptual schematic of the aeration mechanism in ultramafic mining tailings to accelerate carbonation. Figure modified from Power et al. [91].

4.2. In Situ and Ex Situ Carbon Dioxide Removal

Here, we frame EW amongst a range of CDR techniques that are based on similar chemical reactions as for EW. Thus, the reaction between basalt, CO_2 and water, leading to basalt dissolution and carbonation, can be implemented through either an in situ or ex situ CDR approach [25], which can occur at the surface or underground (Figure 5). Natural weathering can be considered a surficial in situ approach. In the underground in situ CDR approach, CO_2 -bearing fluids are circulated through underground basaltic rock formations for the purpose of geological carbon storage [25,97]. EW falls under the category of surficial ex situ approach, involving the spreading of ground rock powder or suitable waste materials on the surface, such as agricultural land or beaches, where chemical reaction occurs with atmospheric CO_2 [25,97,98]. Finally, the underground ex situ approach would involve loose or excavated materials in underground reactors under natural or controlled underground conditions to enhanced weathering and carbonation [97].

An in situ CDR approach means that the reaction with CO_2 occurs directly at the site where the rocks are, without the need for extraction or transportation. This approach offers several advantages. It can be cost-effective because there is no need for mining, grinding, or transport to another location, although it has been suggested that the cost may be similar to that of EW [25]. Moreover, as CO_2 -bearing water is injected into rocks that are in place, there is minimal environmental disturbance, resulting in lower impacts on natural habitats and ecosystems compared to ex situ approaches. Furthermore, with the rocks in place, the reaction with CO_2 can potentially provide long-term carbon storage through the formation of stable carbonate minerals [99]. However, the in situ CDR has its disadvantages, including uncertainties regarding the feedbacks between mineral reactive surface area, reaction rate, and permeability, as well as the size, injectivity, permeability, geomechanical properties, and microstructural characteristics of potential reservoirs for in situ CDR [25].

The ex situ approach of EW involves mining rocks, grinding them into smaller particles, and transporting them to be spread on terrestrial and coastal areas. The EW approach has the advantage that it can be used at sites different from the natural occurrence of the rock material. Moreover, grinding the rocks into a fine powder increases the weathering rate of the material by increasing the surface area of the rock particles [47,100]. Furthermore, the rock powder can be used for targeted applications, such as soil amendment in agricultural

fields to improve soil fertility [38]. However, there are also some disadvantages to EW, including the cost and energy demand associated with mining, grinding and transport of rock material. It is suggested to use clean energy in these processes to increase the overall CO₂ sequestration efficiency of the EW system [95]. Additionally, these activities can have other environmental impacts, such as disrupting local ecosystems or habitats, and they require a large area footprint at the gigaton scale [25].

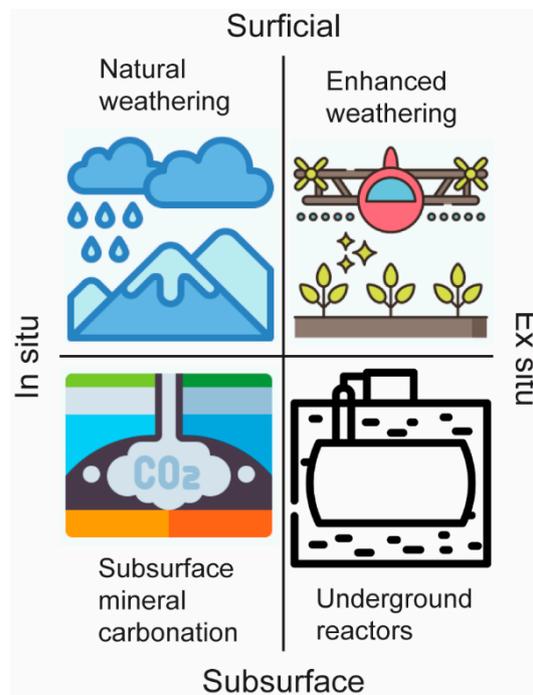


Figure 5. Schematic diagram clarifying enhanced weathering as a surficial ex situ carbon dioxide removal approach, based on subdivision in Bullock et al. [97].

4.3. Rock Selection for EW Implementation

Several factors are taken into account when selecting suitable rock powder or waste for the implementation of EW as a CDR strategy. As mentioned previously, the mineralogical composition of the material used for EW is very important, as its reactivity determines the rate of weathering [30,52]. In addition to mineral reactivity, the abundance and availability of the material are crucial for the scalability and cost-effectiveness of EW. This is of huge importance given a higher abundance increases the scalability, reduces cost, and may decrease distances between mining sites and enhanced weathering sites. Ultramafic rocks with high concentrations of olivine and pyroxene, and those naturally altered to include brucite and serpentine, are favorable for EW due to their high reaction rates and abundant occurrence [24,25]. Multiple studies have examined olivine dissolution rates and olivine carbonation, given the significance of olivine for EW [101,102]. Solution pH, temperature, and reactive surface area are the main factors influencing olivine dissolution rates. It has been observed that the dissolution rate in natural settings decreases over time due to a reduction in the reactive surface area caused by microbial growth or the formation of secondary phases on the mineral surface [102]. These impacts on mineral reactivity need to be considered when applying EW and estimating CDR potential.

Other factors that should be considered, in addition to mineral reactivity and availability, are energy costs and environmental aspects associated with mining, extraction, grinding, and transport of the material to the EW site. Grinding and transport account for 77 to 94% of the energy use, as reported in a UK study on EW [103]. In this context, the utilization of mining waste and other industrial waste has been proposed as an alternative to mining virgin materials for EW applications [12,31,90]. Tailings from platinum group metal (PGM), diamond and asbestos mines generally have a finer particle size distribution (average of

75 μm) compared to chromium, nickel, copper and titanium mines (100–250 μm), which is more favorable for reaction rates [88]. If mining is necessary, environmentally less disruptive mining techniques should be preferred, and rocks that require lower energy for grinding into powder can be considered alongside mineral reactivity [85,104,105]. Ultramafic rocks are reported to require less energy for grinding than mafic rocks, and they have a higher carbon storage potential [103]. Milling the rocks into powder with nanoscale particles increases CO_2 uptake, and mineralogy is the predominant factor controlling CO_2 uptake, with dunite, olivine basalt, pyroxenite, and dolerite rock, exhibiting the highest to lowest uptake, respectively [106,107]. Furthermore, mechanochemical processing of silicate rocks enables chemical adsorption of CO_2 onto the milled rock powders [108]. However, it has been proposed that milling may be unnecessary in EW implementation, as particle size typically has a relatively small effect on net CDR during the initial 10–20 years of implementation [109].

In rock selection, the distance between the rock source or mine and the enhanced weathering site where the rock powder will be applied is also important, because of the cost of transport. Transportation has a significant impact [110], and the use of electric vehicles or hydrogen-powered vehicles could be considered to minimize carbon emissions. Another important environmental aspect to consider is the application of the material on land areas. This is especially relevant in the context of agricultural land, where the minerals need to be compatible with the soil for targeted applications aimed at adjusting soil pH or releasing nutrients to improve soil fertility and stimulate crop growth [38]. Lastly, the choice of material is also evaluated in terms of the overall cost of EW, including mining, extraction, processing, transportation, and application, to assess the economic viability of EW as a CDR technology.

5. Environmental Benefits of Enhanced Weathering

5.1. Carbon Dioxide Removal

The primary objective of EW is to remove CO_2 from the atmosphere as a NET. The dissolution of silicate minerals increases alkalinity, and thus, coastal EW and terrestrial EW, via runoff to rivers and eventually the ocean, cause CDR through the generation of (bi)carbonate ions and alkaline elements. Quantifying the uptake of CO_2 from silicate weathering is not so straightforward, though. Recent research suggested a calculation that takes into account sources of acidity in mineral weathering and the soil environment, other than carbonic acid, which would result in a lower EW carbon uptake [36]. The latter study determined that a correction factor needs to be applied for CO_2 uptake for soils with a pH of less than 6.3, and that EW is not recommended on soils with a pH of less than 5.2 at least not for the purpose of CO_2 uptake.

Moreover, the total EW life cycle carbon emissions and total environmental footprint need to be evaluated. All process stages can be considered in a life cycle assessment (LCA), which was conducted in a study on EW with crushed basalt on agricultural land in Sao Paulo (Brazil) and showed a carbon footprint of 75 kg CO_2 eq per ton of CO_2 eq captured [110]. The study also indicated that transportation was the main factor in carbon footprint, and thus, that distances between the mine site and the agricultural land for EW application should be limited [110]. An LCA of coastal enhanced weathering with silt-sized olivine particles determined a carbon footprint of 51 kg CO_2 eq per ton of captured atmospheric CO_2 [85]. Larger particle size decreases the carbon footprint, but increases the time needed for olivine dissolution, and thus for becoming carbon net negative. The study suggested that the use of renewable energy for olivine comminution and transport, and the use of low-nickel olivine, could minimize the carbon and environmental footprint of EW [85]. Another LCA study applied to EW using mining waste on croplands in Midwestern US revealed a carbon footprint of 41 to 359 kg CO_2 eq per ton of CO_2 captured, and a cost of US\$ 45 to 472 per ton of net CO_2 captured, with the ranges determined by transportation distances and CDR yields [111]. A process-based LCA of the use of waste clay (filter cake) on agricultural land in northeast England showed the potential of 1.62 Mt CO_2 eq captured

through EW for an application rate of 11.2 t/ha, and corresponding carbon footprint of 0.27 Mt CO₂ eq over 26 years [112].

In addition to CDR, modeling studies have shown that EW is effective in reducing ocean acidification, with an estimated global mean surface ocean pH increase by approximately 0.01 relative to baseline by 2100 [113]. The spatial distribution of pH increase would not be uniform but concentrated in South Asia, where extensive EW deployment on agricultural lands and runoff through major rivers in the ocean occur [113]. Tropical forests and croplands are particularly effective areas for EW due to their favorable climate conditions with high temperature and rainfall [19]. The implementation of EW also has a positive impact on reducing the vulnerability of coral reefs, with a decrease from approximately 84% of vulnerable reefs based on aragonite saturation levels in 2100 to about 61% [113]. Terrestrial EW is thought to be more effective in mitigating impacts on coral reef health, including ocean acidification, compared to enhanced dissolution of olivine in open sea environments [19]. Additionally, the supply of silicon (Si) to the ocean through EW may contribute to a decrease in algal blooms and act as an ocean fertilizer, promoting carbon storage through the organic carbon biological pump [69].

5.2. Soil Fertility

Terrestrial EW provides the benefit of land restoration and improved soil fertility [15,38]. Adding rock dust to soil can enhance soil fertility by providing nutrients (such as Mg, Fe, Ca, K, P), adjusting soil pH, and improving cation exchange capacity and electrical conductivity [114]. Basalt, for example, can supply phosphorus, which is generally low in dunite and olivine [41]. Depending on the rock type, particle size, soil type and climate conditions, additional measures can be taken to enhance nutrient release from rock powder and stimulate plant growth. For instance, soils can be inoculated with mineral weathering bacteria [53], which further supports the co-benefits of EW (Figure 6). Microbial weathering can facilitate element mobilization and leaching efficiency [76,115]. Co-deploying humic-like acids in EW can improve nutrient uptake by plants [116]. Studies have demonstrated that basalt rock powder can increase P, Ca and Mg contents, and adjust soil pH to neutral or slightly alkaline levels [117], thereby neutralizing Al and preventing Al toxicity in agricultural production [118]. In addition to CDR, the use of basalt on agricultural soil can also reduce nitrous oxide (N₂O) emissions from crops, likely due to the higher soil pH resulting from basalt application [42].

Andesite rock powder has been utilized as a fertilizer to provide high levels of potassium and phosphorus in soil for eucalyptus growth [119]. Wollastonite powder added to agricultural soil has shown positive outcomes in terms of crop growth, yield and quality [120]. It has resulted in higher silicon uptake in tested crops (lettuce, soybean and spring rye), improving water retention capacity and reducing moisture loss [120]. Silicon can also enhance crop resistance to pathogens, reducing the need for pesticides. Waste mica powder can significantly increase potassium levels in weathered tropical soil [121]. A study with application of 10 kg m⁻² mixed rock powder (of peridotite, serpentine, diabase, plauenite, andesite and basalt in a mass ratio of 1:1:1:1:5) resulted in enhanced crop productivity (7 ± 4.3%) and soil inorganic carbon change (biomass increase of 11 ± 4.6%) in field trials in central China [122]. The latter study suggested that altered soil pH was the main factor influencing higher crop yield, and that water balance (rainfall/evapotranspiration) was the dominating factor on inorganic carbon sequestration. Thus, rock powder represents an important alternative to chemical fertilizers, offering the advantage of lower cost [23]. Moreover, the use of rock powder reduces reliance on (imported) chemical fertilizer, utilizing local natural resources instead [123]. A recent study indicates the promising potential of using basalt rock powder on non-arable soil in South Africa, offering economic benefits and improving food security [124]. Furthermore, the ground silicates can be applied as a liming alternative instead of limestone and dolomite which could release CO₂ upon reaction in slightly acidic soil [125].

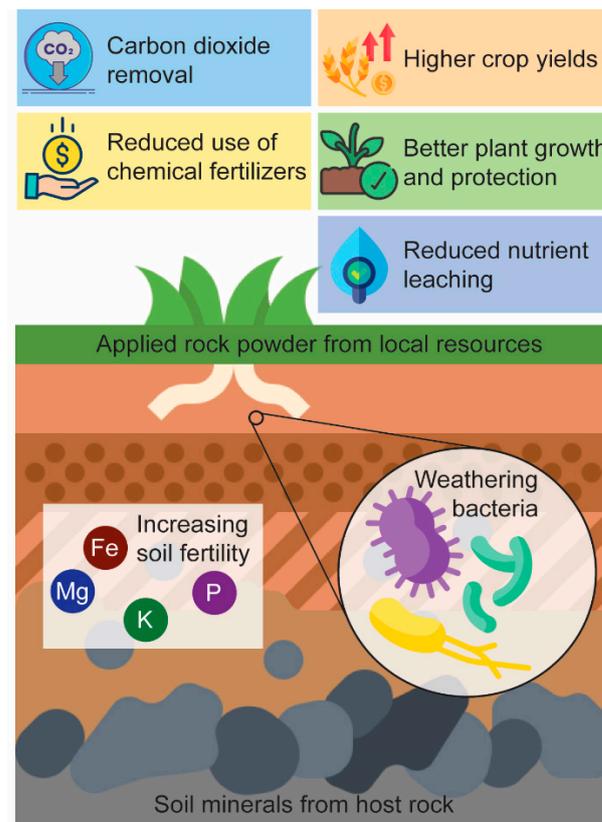


Figure 6. Co-benefits of enhanced weathering applied on agricultural soil and with addition of weathering bacteria. Figure inspired from Ribeiro et al. [53].

In addition to providing nutrient sources and adjusting soil pH, basalt rock dust can increase cation exchange capacity, which is influenced by mineral composition, surface charge, particle size distribution, and surface area [126]. A higher cation exchange capacity means that the soil has a greater ability to retain and exchange nutrient cations because it has more negative surface charges facilitating cation adsorption. Therefore, it reduces nutrient leaching, and improves nutrient cycling within the soil ecosystem. Thus, basalt increases the capacity of the soil to retain cations and it can help in managing highly weathered soils [127,128]. Furthermore, adding rock powder to soil can enhance soil texture, water retention and holding capacity [129]. It is crucial to consider those soil properties as soil water content significantly influences crop growth [130]. The hydraulic properties of soil depend on several factors, including the amount of rock powder applied, the intrinsic grain properties and texture of the soil, and the organic matter content. EW plays a significant role in managing water retention in topsoils [130]. Incorporating ground rock into soil can improve soil aggregation, leading to increased porosity, improved aeration, and enhanced water infiltration [131]. This contributes to higher water holding capacity and reduced water runoff. Improved soil structure facilitates root penetration and nutrient uptake by plants, promoting crop growth [132]. Furthermore, EW offers synergies with afforestation and reforestation, where EW can be applied to supply nutrients to afforestation and reforestation areas [130,133]. Additionally, EW and afforestation contribute to CDR by providing alkaline minerals, which results not only in uptake of CO_2 in water in the form of bicarbonate and carbonate ions that run off from land to rivers and eventually in the ocean, but also in an increase of soil fertility which enhances the growth of plants, which take CO_2 from the air leading to carbon sequestration through photosynthesis. An overview of potential synergies between EW, biochar, afforestation, and bioenergy with carbon capture and storage, based on Amann and Hartmann [18], is presented in Figure 7.

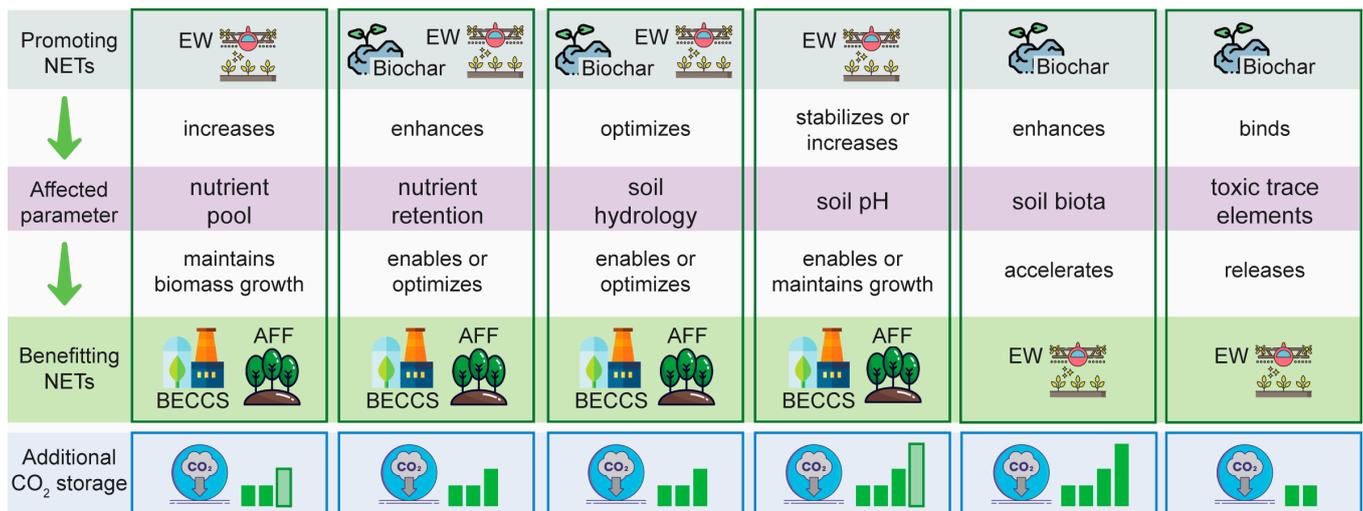


Figure 7. Schematic overview of the synergies between enhanced weathering (EW), biochar, afforestation (AFF) and bioenergy with carbon capture and storage (BECCS). Figure modified from Amann and Hartmann [18].

6. Potential Impact on Ecosystems and Biodiversity

The implementation of EW should not cause harm, and therefore, its potential effects on terrestrial and marine ecosystems must be carefully assessed.

6.1. Terrestrial Ecosystems

In terrestrial systems, EW provides nutrient supply, adjusts soil pH, and enhances soil structure, leading to improved soil fertility and nutrient cycling [15,38]. Although the impact of rock dust on soil ecosystems and biodiversity under EW has not been extensively studied, insights can be gained from research on synthetic mineral fertilizers. Generally, higher phosphorus or potassium content in the soil favors bacterial, invertebrate, and tree diversity, but may have negative effects on grassland communities [45,134]. Studies have indicated that the application of mineral fertilizer improves soil enzymatic activity and enhances soil biodiversity [135]. Soil microbial diversity contributes to crop productivity and soil nutrient retention capacity, but it can be negatively impacted by land-use intensification, such as the use of chemical fertilizers [136]. Mineral fertilizer application can disrupt natural systems and reduce organic nitrogen uptake [136]. In forest soil ecosystems, fertilizer amendment has been shown to have long-lasting effects on soil microbial diversity [137]. Excessive nutrient loading, particularly nitrogen and phosphorus, into water bodies through leaching can lead to eutrophication, characterized by algal blooms and low oxygen levels, which can harm fish populations [138]. Additionally, increased phosphorus availability can negatively impact plant biodiversity, as observed in tropical forests [139]. However, EW using natural minerals or rock dust has the advantage of slower nutrient leaching compared to conventional fertilizers, making the soil less susceptible to nutrient runoff [82].

Changes in soil conditions resulting from EW may favor the growth of certain plant species over others, potentially altering the composition of plant communities. Shifts in microbial diversity and abundance in soil can also impact plant diversity [140]. Similar effects on ecosystem processes and biodiversity have been observed due to global warming, temperature changes, and variations in soil moisture, favoring shrubs over grass in the Colorado Plateau [141]. Furthermore, plant diversity influences the microbial communities in the soil, with bacteria primarily affected by plant diversity and fungi predominantly influenced by plant-derived organic matter inputs [142]. Plant species diversity can also influence soil hydraulic properties, affecting water distribution and availability [143].

6.2. Marine Ecosystems

In terms of impact on marine ecosystems, we have mentioned that EW leads to the generation of (bi)carbonate ions and alkaline elements from mineral dissolution that runoff to the ocean. A slight increase in alkalinity can help mitigate acidification caused by increased atmospheric CO₂ levels. Changes in alkalinity should be carefully managed, though, to avoid adverse impacts. Excessive alterations in alkalinity should be avoided, and pH levels should be monitored to protect marine ecosystems and prevent shifts in biological communities. Moreover, the addition of rock powder in coastal areas may cause sedimentation, potentially affecting water clarity, light penetration, and the quality of aquatic habitats (Figure 8). Bach, et al. [144] proposed that local alkalinity “hotspots” or gradients could be created where rock material is distributed, and the response of different ecosystems to these hotspots would require investigation. Phytoplankton growth may be slower at such hotspots, but these effects are considered local and temporary [144]. Studies have indicated significant, but generally moderate, impacts on various groups in the phytoplankton community and heterotrophic bacteria, even with a 21% increase in inorganic carbon sink in the ocean resulting from alkalinity increase [145]. However, increasing seawater alkalinity has more pronounced effects on the diatom community due to decreased biogenic silica build-up [145]. If silicate materials are used in EW, they can provide a supply of silicon, which could be beneficial for silicifiers such as diatoms [144]. Biogeochemical modeling indicates that the use of natural sources like basalt and olivine has very low CDR efficiency and significantly disturbs marine food quality by decreasing the relative organic matter content of aggregates, leading to a significant reduction in zooplankton feeding and fecal pellet production [86].

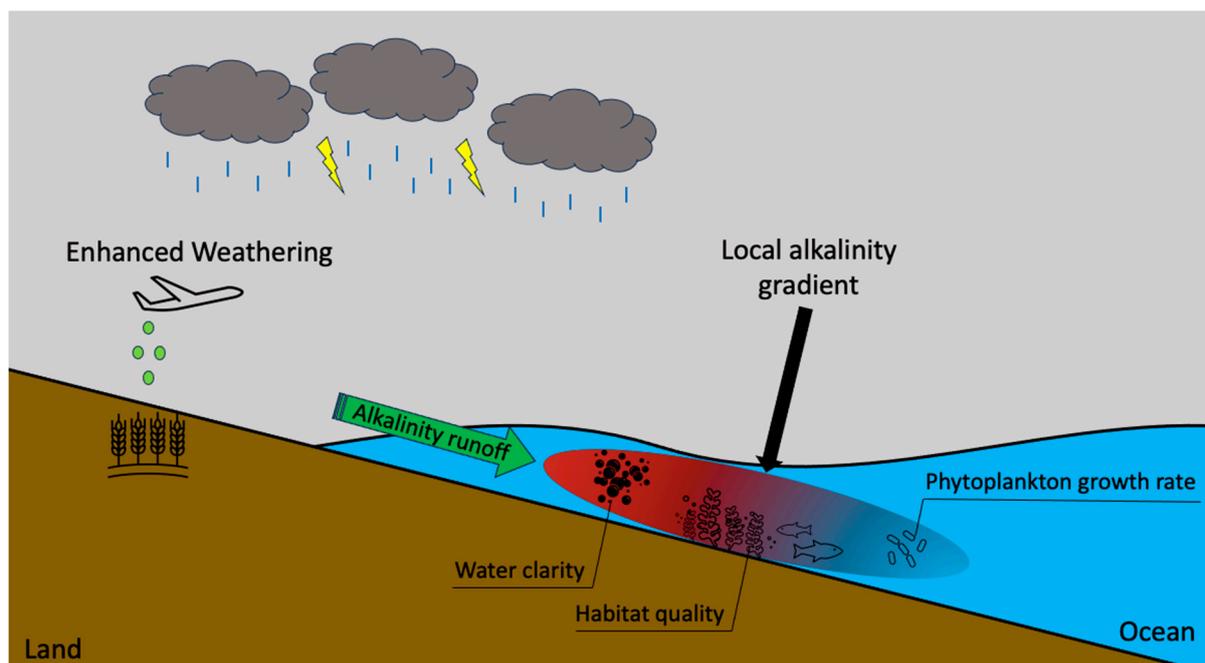


Figure 8. Conceptual schematic of potential effects of EW on marine ecosystems.

Water quality and contamination will be discussed in the next section on “Water and air quality considerations”. Monitoring and managing water quality are crucial to prevent pollution and negative impacts on aquatic organisms and ecosystems. The use of olivine powder in EW may release some nickel [69]. However, laboratory studies have shown that marine phytoplankton species are not highly sensitive to nickel concentrations under the conditions applied in the experiments, where the use of nitrate and synthetic organic ligands may mitigate the negative impact of nickel on species growth [146]. Based on marine environmental quality standards, a study suggested that 0.059 to 1.4 kg of

olivine per m² of seabed, depending on local sedimentary Ni concentrations, could be applied without any risk of negatively impacting benthic biota [147]. Moreover, risks on contamination can be mitigated by careful examination of the rock materials used in EW [144] and by considering the amounts applied and their frequency. Industrial waste, such as steel slag, may contain elements such as chromium, molybdenum, lead, and nickel, which are harmful above critical threshold levels [12]. Dunite rock, mainly composed of olivine mineral, can contain nickel, which is relatively soluble in seawater [17], and eukaryotic microalgae are relatively sensitive to high nickel concentrations compared to prokaryotes like cyanobacteria [144].

Interactions between ecosystems play a crucial role, as changes in nutrient supply associated with EW can influence primary productivity and ecosystem dynamics in the marine environment. Alterations in nutrient levels and ratios have the potential to impact phytoplankton communities, thereby affecting higher trophic organisms. Moreover, terrestrial and marine ecosystems are interconnected, and changes in nutrient supply resulting from terrestrial EW ultimately have consequences for marine ecosystems through runoff in rivers and, eventually, the sea. Evaluating the effects of EW on ecosystems requires assessing ecological connectivity and implementing an integrated ecosystem management approach to minimize potential negative impacts and ensure overall ecosystem integrity.

7. Water and Air Quality Considerations

7.1. Water and Soil Quality

Implementation of EW can lead to an increase in alkalinity, resulting in higher soil and water pH and the provision of nutrients. This is particularly beneficial for application on highly weathered soils [118]. However, there is also a potential for the release of toxic trace elements and radionuclides, which should be carefully considered [148]. The previous sections have discussed the beneficial impact of pH increase and potential adverse effects on ecosystems. Modeling studies have indicated a low risk of negative effects on water quality due to phosphorous leaching from basalt in EW for most aquatic systems [45]. However, the release of trace elements through EW could have implications for both marine ecosystems and human health, particularly if toxic trace elements were released into agricultural soil and drinking water. The release of these elements is directly linked to the properties of the mineral material used in EW, such as its bulk composition, total reactive surface area, and reactivity. Comparisons between common materials used for EW, such as dunite, olivine and basalt, have shown variations in weathering efficiency and the presence of toxic trace elements such as Ni and Cr [10,80]. Basalt may contain larger amounts of other metals like Pb and Zn [3]. The release of Ni, in particular, is a concern of EW with olivine as it could affect the soil ecosystem and be transported to the ocean via rivers, potentially impacting marine species [144]. Life cycle assessments have shown that the main environmental impact of coastal EW with silt-sized olivine comes from fuel dependent electricity required for grinding olivine, followed by the release of Ni [85]. The Ni release can lead to Ni accumulation in soils and crops [80], affecting plant growth [149]. Studies have indicated that Ni and Cr concentrations in soil, surface, spring, and well water in ultramafic formations and mines are generally below detectable levels [25,150]. Moreover, existing phytoremediation strategies could be applied to prevent the accumulation of Ni and Cr in soils, by using hyperaccumulating plants as part of crop rotation [151].

Quantitative simulation approaches assessing trace element accumulation for suggested application rates of basalt powder (of 40 t ha⁻¹ yr⁻¹) indicate potential constraints on the feasibility of EW due to environmental regulations on toxic trace elements concentrations, emphasizing the need for further study on elements such as Cu, Cr, Ni, Zn and V [152]. Few experiments have reported the actual release of toxic trace elements from EW in soil and pore water. Mesocosm experiments using agricultural soil and ground dunite have shown elevated levels of Ni and Cr in soil solution, with Ni contents exceeding the threshold for drinking water quality of 0.02 mg L⁻¹ but within the limit for agricultural

irrigation water of 0.2 mg L^{-1} [41]. In contrast, another mesocosm study with *Solanum tuberosum* on alkaline soil amended with 50 t/ha of basalt showed an increase in soil and pore water Ni concentrations, which remained below regulatory threshold levels [153]. Similarly, a study on EW with the application of 100 t/ha of basalt on agricultural soil in the UK demonstrated that the concentrations of dissolved toxic trace elements such as Ni, Cr and V were all below the regulatory thresholds for drinking water [43].

The leachability of toxic trace elements is a major concern when using industrial waste, such as mine tailings, steel slag, fly ash, and concrete demolition waste. Concrete contains trace elements such as antimony, barium, lead, chromium, molybdenum and vanadium, that are chemically bound in hydrate phases but could potentially become mobile during EW [154]. Steel slag raises concerns regarding the potential leaching of toxic trace elements during EW [155]. The release of more calcium from ferrous slags in base metal production than nonferrous slags has been suggested, with the former being more suitable for EW, whereas the latter may release more toxic trace elements along with acidity due to sulfides [148]. Thus, this environmental concern is an impediment to the application of such waste materials for EW technology.

7.2. Air Quality

Apart from the potential release of toxic trace elements into soil and water during EW, the effects on air quality must also be considered. Concerns have been raised regarding the grinding of rocks or minerals into fine powder or dust and their subsequent spreading them on land. The crushing and grinding process can generate fine particles with sizes smaller than $2.5 \mu\text{m}$, while mine tailings can contribute to the emission of coarser particles in the 2.5 to $10 \mu\text{m}$ range [156,157]. The dispersal and transport of dust in the air are influenced by particle size and weather conditions, such as humidity and wind speed. Weather conditions during the spreading of materials on land, particularly when helicopters or fixed wing aircrafts are used, are crucial factors [45,72]. Fine particles remain suspended in the air for longer periods and can be more easily inhaled. Particles smaller than $10 \mu\text{m}$ in diameter, especially those smaller than $2.5 \mu\text{m}$, pose risks for human health [69]. Airborne dust particles can cause irritation to respiratory tracts, worsen symptoms for asthmatic patients, and increase the risk of respiratory infections. The smallest particles, less than $2.5 \mu\text{m}$, are of particular concern as they can penetrate deep into the lungs and potentially enter the bloodstream. Additionally, fibrous serpentine minerals (asbestos) in some ultramafic rocks present health risks [19,25], as inhalation of asbestos fibers can increase the risk of lung cancer [158]. To minimize health and safety risks, as well as reduce energy costs associated with comminution, implementing EW with coarser particles is recommended [109]. An analysis of EW technology in twelve nations indicated that higher CDR potential is accompanied by increased environmental and health impacts in the supply chain, encompassing mining, grinding, distribution, and spreading of rock dust [6]. Striking a balance and achieving compliance with regulatory standards will be crucial for the advancement of EW technology.

To mitigate potential effects on air quality and human health, appropriate mitigation measures should be implemented. These may include the use of personal protective equipment, such as respiratory masks, site design with windbreaks and vegetative cover, and dust suppression techniques like water sprays [159]. Carbon mineralization has been proposed as a method to mitigate the health risk associated with asbestos in ultramafic mining tailings [28]. Furthermore, monitoring dust emissions and air quality is essential to ensure compliance with regulatory standards.

8. Other Potential Risks and Challenges

The large-scale implementation and long-term stability of EW face several challenges that must be carefully addressed. The primary challenge is scaling up from lab-scale experiments to pilot-scale demonstrations and large-scale deployment. Significant infrastructure and resources are required for the extraction, processing, transportation, and application

of large quantities of rock dust. Therefore, identifying cost-effective methods and economically viable rock sources is crucial. Technological innovations in mineral processing, grinding methods, and application techniques may be necessary to enhance the efficiency and effectiveness of EW by optimizing the mineral weathering process and maximizing CDR rates. The rock sources or industrial waste sources should be abundantly available and easily accessible near the sites of EW deployment. Environmental impacts associated with rock extraction, processing, energy consumption, application, and potential release of contaminants that may impact ecosystems must be mitigated. Adequate monitoring of soil, water and air quality is essential and should be implemented and managed. Some recent or on-going large-scale field trials have indicated successful EW and CO₂ uptake results. For example, results from the first three years of an ongoing EW field trial with application of 50 t ha⁻¹ of crushed silicate rock on an oil palm plantation in Sabah, Malaysia quantified CO₂ uptake at up to about 0.4 t CO₂ ha⁻¹ yr⁻¹ higher than the reference catchments based on alkalinity export [160]. A field trial with the application of 10 kg m⁻² mixed rock powder on farmland in central China reported net carbon storage of 4.3 ± 0.8 t CO₂ ha⁻¹ over a period of three years based on soil inorganic carbon measurements [122]. Long-term stability needs to be ensured, and measures should be in place to prevent carbonate mineral dissolution and the release of CO₂ back into the atmosphere. Such measures may involve monitoring and maintaining an alkaline pH of the soil and water, since carbonate, in particular CaCO₃ and hydrated magnesium carbonate minerals, can dissolve in more acidic environments. It is worth noting that moderate application of basalt rock powder on peat soils through EW could potentially lead to soil CO₂ emissions and leaching of dissolved organic carbon (DOC) due to pH changes, as illustrated in Figure 9 [161].

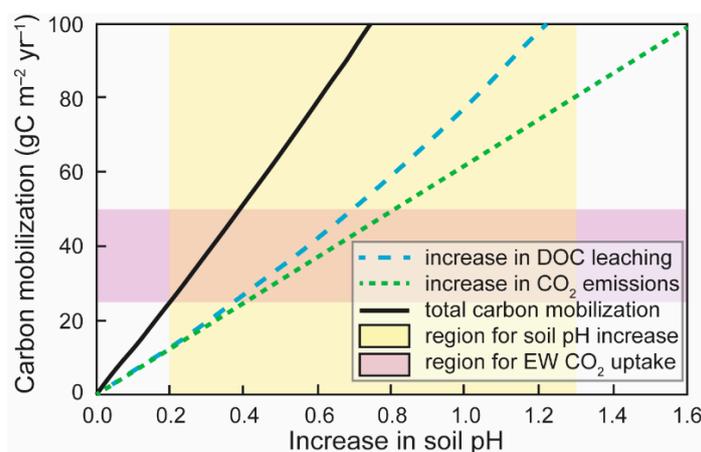


Figure 9. Carbon mobilization versus increase in soil pH for basalt application of 1 kg m⁻² yr⁻¹ on peat soils. Figure adapted from Klemme et al. [161].

Policy and regulatory frameworks need to be established for the large-scale implementation of EW. Therefore, monitoring and verification methods need to be agreed, and it is not clear yet whether this should be based on analysis of soil water, solids or gas, remote sensing, or all or a combination of those, and which range of parameters and analyses should be investigated [125]. In particular, there are two pathways for carbon storage via EW, either through bicarbonate ions in water, or via precipitation of carbonates, depending on soil and climate conditions, and this will need to be considered in carbon accounting and monitoring and verification [125]. Clear guidelines, incentives, and a favorable investment environment should be provided to promote the deployment of EW technology [162]. Integrating EW into international and national climate policies, carbon markets, and funding mechanisms will facilitate its adoption and contribute to long-term sustainability [16]. Moreover, social acceptance and engagement from stakeholders are crucial for the successful implementation of EW [163–165]. Addressing potential concerns and involving local communities and other stakeholders in decision-making processes

are critical steps [109]. Transparent communication is key, and awareness campaigns can foster understanding and support for EW projects. Another potential challenge could be interference with other land uses, but EW can be co-deployed, giving it an advantage compared to other CDR technologies [45]. In addition, it has co-benefits for agricultural land and degraded land. However, establishing long-term CDR monitoring and liability frameworks and mechanisms is necessary to ensure responsible management of stored carbon and to address any unintended consequences. These actions are essential for the sustainable implementation of EW technology.

9. Integration with Sustainable Development Goals

The CDR strategy of EW aligns well with several Sustainable Development Goals (SDGs) outlined by the United Nations (Figure 10). EW's primary goal is linked to SDG 13, Climate Action. By removing CO₂ from the atmosphere and potentially reducing also other greenhouse gas emissions from the soil, EW can help limit global warming. The process of making acidic soil neutral or slightly alkaline through EW can help reduce soil CO₂ efflux [166]. In the EW process, energy requirements for mining, grinding, transportation, and application should be minimized and based on clean energy to avoid carbon emissions and achieve significant negative emissions using EW technology. Therefore, EW aligns with the goals of seeking climate resilience and developing low-carbon pathways.

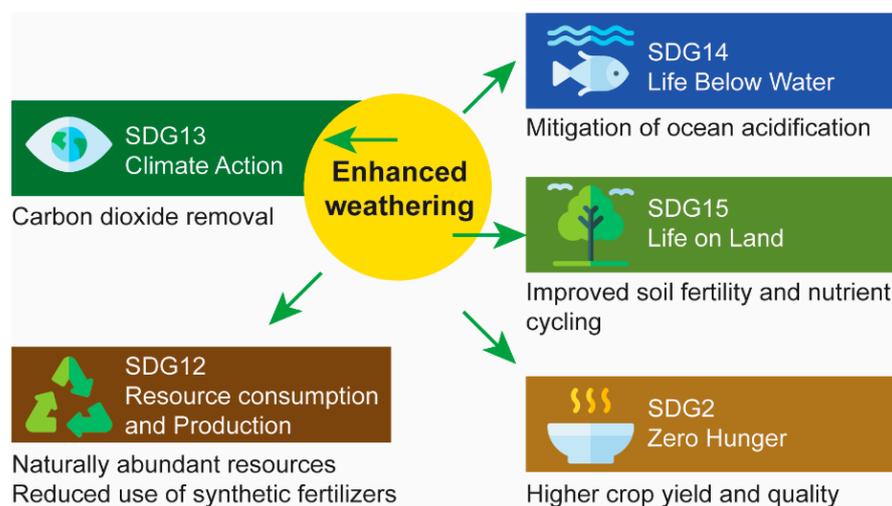


Figure 10. Schematic diagram showing how enhanced weathering can contribute to several Sustainable Development Goals (SDGs).

The implementation of EW as CDR strategy comes also with co-benefits regarding other sustainability objectives. EW technology supports SDG 14, Life Below Water, and SDG 15, Life on Land, since it can help increase the alkalinity of water, and thus assist in mitigating ocean acidification caused by increasing atmospheric CO₂ levels. This buffering effect can help protect marine ecosystems, coastal communities, and biodiversity. It is particularly important for preventing the degradation of coral reefs, which are susceptible to decreasing pH levels that affect aragonite saturation levels in the ocean. Moreover, higher silicon concentrations stimulated by EW may promote diatom growth over algae [15]. EW can improve soil fertility and nutrient cycling, which may result in higher crop yields and quality. It can also promote land restoration and biodiversity conservation, positively impacting ecosystems and sustainable land management. However, the potential expansion of mining to deliver materials for EW should be carefully considered to minimize negative effects on biodiversity and ecosystems [166].

The use of naturally abundant and widely available rocks or minerals in EW aligns with SDG 12, Responsible Consumption and Production. This approach reduces reliance on limited resources. Moreover, EW utilizes these natural resources efficiently, aiming to

improve soil fertility and to reduce the amount of soil amendments needed. It can provide an advantageous alternative to more expensive and less accessible synthetic fertilizers, especially in less developed countries. Additionally, as EW increases soil alkalinity alongside soil fertility and nutrient cycling, liming soil treatment may no longer be necessary, reducing the need for calcium carbonate production [167].

Since EW can enhance soil fertility in agricultural land, it could be considered that EW may also contribute to SDG 2, Zero Hunger. The addition of rock dust can provide nutrients, neutralize soil acidity, restore the Si pool available to plants (which helps increase pest resistance), and increase soil cation exchange capacity. Silicate resources may be locally available and abundant in poorer areas where ensuring crop growth is crucial for avoiding hunger. Increasing crop yields through the use of cost-effective soil amendments could improve societal access and increase yields [168]. Thus, EW supports sustainable agriculture and can contribute to food security.

There are also several trade-offs associated with the implementation of EW. A primary concern is the energy and resource requirements for EW implementation. As energy is required, SDG 7, Affordable and Clean Energy, is also relevant. Grinding and transportation of rock (powder) are energy-intensive processes that could involve carbon emissions. This trade-off can be mitigated by effectively managing the network from rock source to field application, employing balanced comminution or utilizing rock waste, and relying on clean renewable energy sources. Note that the remote location of some mining sites may put some constraints on these options.

Another concern is the potential release of contaminants, particularly toxic trace elements, from the rocks or minerals applied for EW on land, as well as potential air pollution. This aspect may impact SDG 3, Good Health and Well-being. Careful management and monitoring of water and soil quality are necessary, and appropriate rocks should be selected to minimize this trade-off. Moreover, robust monitoring systems are required to assess the CDR effectiveness, co-benefits, and potential environmental impacts of EW.

10. Conclusions

Enhanced weathering has emerged as a promising CDR strategy with potential environmental benefits. Various factors, such as rock selection, particle size, reactive surface area, soil microbial processes, and climatic conditions, influence its effectiveness. Ultramafic rocks with high reactivity are particularly suitable for EW. The CO₂ dissolution in the water, mineral dissolution and carbonate precipitation reactions are influenced by factors like temperature, rainfall, and pH. Feedback loops can either amplify or decrease the effects of EW. Implementation techniques include rock grinding, direct rock spreading, and utilization of mining and industrial waste. Considerations for rock selection include reactivity, availability, energy costs, and environmental aspects.

This review paper has highlighted the environmental considerations of EW, focusing on CDR, alkalinity generation, soil fertility, potential impact on ecosystems and biodiversity, and water and air quality considerations. EW can effectively remove CO₂ from the atmosphere, and may offer land restoration and improved fertility. However, potential impacts on terrestrial and marine ecosystems must be carefully examined. Terrestrial EW can affect soil conditions and nutrient availability, influencing plant communities and microbial diversity. Managing nutrient supply is important to maintain balance in natural systems. In marine ecosystems, EW could mitigate ocean acidification but requires careful management to prevent adverse effects on biodiversity.

Water and air quality considerations are vital in EW implementation. Monitoring and managing water and air quality are crucial to prevent pollution. The selection of rock material for EW should avoid the release of toxic trace elements, with careful assessment of potential impacts on human health and ecosystems. Dust emissions during grinding and application should be mitigated to minimize air pollution and health risks.

Large-scale implementation of EW faces challenges such as scaling up from lab-scale experiments, identifying cost-effective rock sources, addressing environmental impacts,

ensuring long-term stability, establishing policy frameworks, gaining social acceptance, and implementing monitoring and liability frameworks.

Overall, EW has the potential to be a sustainable CDR strategy with environmental benefits, and some contribution to the SDGs. Careful planning, monitoring, and management are crucial to ensure the effectiveness of EW and minimize any potential negative impacts.

11. Future Perspectives

Further research on EW is crucial to enhance our understanding of the underlying mechanisms, environmental impacts, and feedback loops associated with this approach. A deeper insight will enable more accurate predictions of the potential impacts of EW implementation, better estimation of CDR potential, and improved assessment of the long-term viability of EW.

Currently, most experimental studies on EW are conducted at the laboratory scale, primarily focusing on weathering rates of minerals only. However, it is known that microbial activity can accelerate these rates, and further studies are needed to investigate mineral weathering in soil conditions. Field studies conducted at larger scales and in real-world conditions are necessary to advance our understanding of EW. This requires interdisciplinary research that spans the fields of geochemistry, soil science, plant science, microbiology, and climate science. Field studies, along with associated modeling, will facilitate the estimation of CDR rates and help quantify the long-term carbon sequestration potential of EW at different scales. Additionally, a deeper understanding of the weathering and carbonation mechanisms in soil will contribute to the improvement and optimization of this technology.

More research is required to better understand the effects of EW on soil and water quality. Previous studies have indicated the potential release of toxic trace elements, such as nickel and chromium, from the application of certain materials like dunite and olivine. This has led to a shift in focus towards the application of basalt as soil amendment on agricultural land. It is necessary to gain a better understanding of the leaching potential of toxic trace elements from various material sources, including rocks, minerals, mine waste, and industrial waste. This knowledge is essential for identifying potential environmental risks and establishing limitations on the application and implementation of specific source materials.

Although a few papers have highlighted the potential negative impact of fine rock or mineral dust from EW on air quality and human health, there are no specific studies dedicated to investigating this aspect, as far as the authors are aware. Studies on the impact of small particles in air on human health has mainly focused on particles generated from combustion, such as soot and exhaust particles. Research on air pollution from mining activities is relatively scarce, although occupational airway and lung diseases are common among miners. Conducting studies to assess the impact of spreading rock dust particles over terrestrial or coastal areas on human health would provide valuable insights into potential hazards and could potentially establish guidelines on mineral particle size limitations for EW.

The long-term impact of EW on terrestrial and aquatic ecosystem dynamics needs to be further documented through experiments and trials, initially on smaller scale and following significant laboratory testing to ensure minimal environmental harm. Subsequently, pilot-scale and long-duration tests in real field settings will be necessary to fully assess potential impacts on ecosystems and determine safe rock types and application rates. Furthermore, a more detailed investigation of the feedback loops associated with EW is essential. Positive and negative feedback loops have already been identified, but given the complexity of the interactions between mineral dissolution, water chemistry, microbiological and plant communities, atmospheric conditions, and climate, a comprehensive understanding of these feedback loops is imperative.

Exploring synergies or trade-offs between EW and other CDR technologies is also necessary. Synergies between different CDR methods could enhance cost efficiency and

increase CDR rates. Particularly, investigating synergies between EW and microbial carbon fixation, afforestation or reforestation, and tailored artificial soil creation is of high interest. Understanding these synergies or trade-offs will facilitate the optimization of integrated climate solutions and avoid unintended environmental consequences.

The implementation of EW will require the development of policy and regulatory frameworks. Integration of EW into national and international climate policies, carbon markets, and funding mechanisms is essential. Additionally, efforts must be made to gain social acceptance and engage stakeholders. Long-term monitoring and verification protocols should be established to assess the effectiveness of EW projects, including measuring CO₂ uptake, recording potential changes in soil and water chemistry, and monitoring potential leakage or release of stored CO₂. Moreover, liability frameworks should be developed to ensure responsible carbon management and the sustainable implementation of EW.

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