

# Basaltic Rock Weathering as an Atmospheric CO<sub>2</sub> Removal (CDR) Technique: A Review

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## Abstract

Atmospheric CO<sub>2</sub> concentrations have reached significant levels during the industrial era, necessitating the implementation of effective carbon dioxide removal (CDR) technologies. Enhanced Rock Weathering (ERW) using basalt has emerged as a high-potential strategy, leveraging its mafic composition to sequester CO<sub>2</sub> as stable carbonates. This review analyzes ERW's geochemical processes, application methods, and multifaceted co-benefits, such as restoring “background fertility” and improving soil structure. The literature indicates that while small-scale applications range from 1.5 to 6 Mg·ha<sup>-1</sup>·yr<sup>-1</sup>, intensive agricultural rates typically reach 40–100 Mg·ha<sup>-1</sup>·yr<sup>-1</sup>. Global models estimate a sequestration potential of up to  $4.9 \times 10^9$  Mg CO<sub>2</sub>·yr<sup>-1</sup> for basalt, although field-scale results vary significantly, reaching uptake rates of up to 4 Mg CO<sub>2</sub>·ha<sup>-1</sup> depending on pedological conditions and crop types. Despite this promise, transitioning to large-scale deployment faces critical hurdles, including operational difficulties in mechanized spreading and a scarcity of audited, long-term field data. Future research must prioritize standardized protocols and comprehensive economic analyses to bridge the gap between theoretical models and empirical evidence. Ultimately, ERW represents a multifaceted solution for climate stabilization and sustainable food security, provided that sequestration efficacy and environmental safety are rigorously verified through high-application field trials.

**Keywords:** carbon stock; enhanced weathering; geochemical monitoring; soil carbon sequestration; soil chemical weathering; soil organic carbon

## 1. Introduction

Despite the ongoing research needs within the scientific community regarding climate change and global warming, a primary challenge of the current century on a global scale remains the abatement of industrial CO<sub>2</sub> emissions. The International Energy Agency (IEA) posits that the objectives delineated in the Paris Agreement can be attained by maximizing the practical thresholds of extant climate mitigation technologies [1]. The Paris Agreement [2] underscores the imperative necessity of implementing comprehensive and ambitious frameworks to address anthropogenic climate change, thereby fostering a sustainable trajectory for the future.

To effectively address the impacts stemming from global warming, various atmospheric carbon management technologies have been developed in recent years. Notable

Academic Editor: Cezary Kabala

Received: 27 May 2026

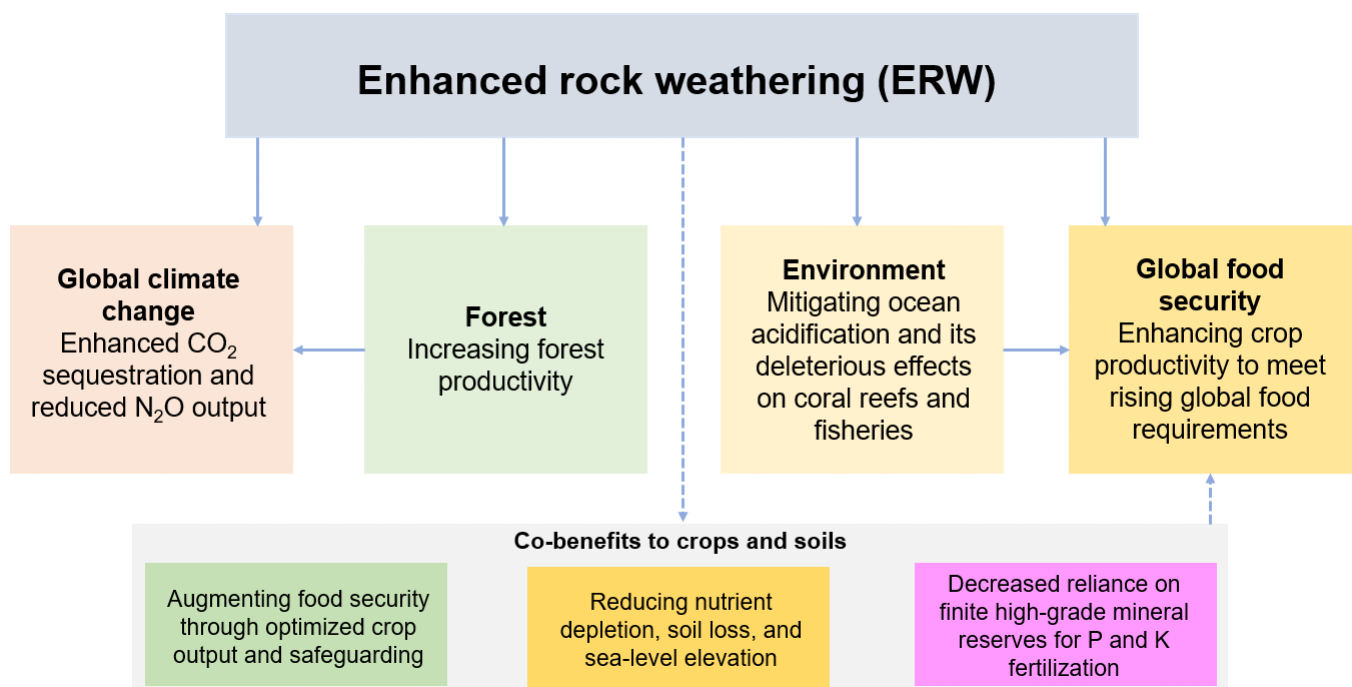
Revised: 22 June 2026

Accepted: 25 June 2026

Published: 26 June 2026

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among these are Negative Emission Technologies (NETs), which encompass measures designed to sequester anthropogenic CO<sub>2</sub> from the atmosphere for subsequent storage—within pedological sinks, biomass, or oceans—or for industrial utilization. Consequently, NETs hold significant potential for climate change mitigation [3]. A prominent strategy within this framework is Enhanced Weathering (EW) [4], a process involving the controlled and accelerated dissolution of silicate minerals found in rocks such as basalt. This mechanism captures atmospheric CO<sub>2</sub> and incorporates it into the soil matrix as pedogenic inorganic carbon [3,5,6] (Figure 1). Furthermore, the application of these finely pulverized minerals to the soil enhances primary productivity in both agricultural and natural ecosystems [7–10]. It also aids in minimizing nitrogen leaching, thereby synergistically improving organic carbon sequestration in both biomass and the soil profile.



**Figure 1.** Enhanced rock weathering offers a robust framework to mitigate contemporary global challenges, including climate change, broader environmental degradation, forest health, and food security (modified from [7]).

In this regard, carbon capture and storage (CCS) is positioned as a pivotal technology for achieving the objectives delineated in the Paris Agreement [11,12]. Given the inherent capacity of pedological systems to sequester and retain carbon dioxide, soils constitute a critical carbon reservoir within the global cycle, thereby playing a significant role in climate change mitigation.

Indeed, soils represent the largest terrestrial carbon reservoir, sequestering approximately three times more carbon than aboveground biomass and doubling the amount currently held in the atmosphere [13]. Enhancing soil organic carbon (SOC) stocks within agricultural lands is recognized as a high-potential strategy for carbon dioxide removal (CDR) [14], thereby offering a substantial contribution to climate mitigation [15]. This becomes particularly significant considering that, according to the FAO, croplands and managed pastures account for 37% of the Earth's total land surface [16].

Basalts, and basaltic formations in general, possess the capacity to sequester CO<sub>2</sub> in quantities exceeding those of other geological reservoirs, primarily due to their high chemical reactivity [17,18]. In essence, the reactive mineral phases inherent in basalt facilitate relatively rapid and effective mineral carbonation, leading to permanent and efficient

CO<sub>2</sub> storage [1,19]. Mineral reactivity plays a crucial role in the CO<sub>2</sub> carbonation process [20–22]; consequently, the higher the mineral reactivity, the more effectively the process progresses [23]. Consequently, CO<sub>2</sub> storage in basaltic rocks is currently regarded as a promising frontier that opens novel research avenues. Specifically, several scholars report that mafic lithologies offer among the highest potentials for CO<sub>2</sub> sequestration [24–27]. The mineral carbonation process occurs through the interaction of dissolved CO<sub>2</sub> with the host rock, particularly natural rocks of mafic or ultramafic composition. The CO<sub>2</sub>-charged rainwater is acidic (typically exhibiting a pH range of 3–5). This acidic lixiviant promotes the hydrolytic dissolution of cation-bearing silicate minerals.

Although geological CO<sub>2</sub> storage in basaltic formations and soil-based enhanced rock weathering operate at different spatial scales and under distinct deployment conditions, both rely on the same fundamental geochemical principle: the dissolution of mafic silicate minerals, the release of divalent cations (such as Ca<sup>2+</sup>, Mg<sup>2+</sup>, and Fe<sup>2+</sup>), and the subsequent stabilization of carbon as carbonate minerals or dissolved inorganic carbon species. Therefore, geological carbonation studies provide a valuable mechanistic basis for understanding the potential of basalt amendments in soils, though their effectiveness under field conditions must be assessed independently.

While these processes are still in an incipient stage, carbon sequestration through the carbonation of basaltic rocks represents a novel pathway for CO<sub>2</sub> capture. In this regard, Almaraz et al. (2022) have recently posited that terrestrial silicate weathering plays a pivotal role in regulating global atmospheric CO<sub>2</sub> levels [28]. Some authors report that mineral carbonation requires the coupling of CO<sub>2</sub> with divalent metal cations, resulting in the precipitation of carbonate minerals—specifically calcite (CaCO<sub>3</sub>), dolomite (CaMg(CO<sub>3</sub>)<sub>2</sub>), magnesite (MgCO<sub>3</sub>), and siderite (FeCO<sub>3</sub>)—[29–32]. Consequently, the availability of divalent cations for carbonate precipitation is essential. Within this context, it is widely recognized that basaltic and ultramafic rocks exhibit high dissolution rates. These intensification methods are detailed by [33]. Specifically, Schaef et al. reported that basalt contains approximately 25% by weight of calcium, magnesium, and iron oxides (comprising 7–10% wt% Ca, 5–6% wt% Mg, and 7–13% wt% Fe) [34].

Although various experiments involving the application of crushed basalt to agricultural and forest soils have been conducted [35,36], further testing of this technique across diverse soil types, land uses, and climatic conditions remains essential to cross-reference results and more consistently evaluate the method's efficacy. Furthermore, it is necessary to assess different management options and quantify potential side effects [37], most notably the introduction of heavy metals present in the amended material into ecosystems [5,38].

The present study provides a comprehensive review of the literature and prior experimental data concerning enhanced basaltic rock weathering as an atmospheric CO<sub>2</sub> removal (CDR) technique, outlining its inherent effects, advantages, and limitations. By synthesizing the reviewed publications, this work addresses the following research questions: What are the fundamental characteristics of basaltic rocks that facilitate its application in enhanced weathering? What is the nature of the basalt weathering process? What is the overarching significance of enhanced weathering processes? What does mineral carbonation entail, and how is it linked to basalt weathering? What additional co-benefits does the application of basaltic rocks provide for soil health and properties?

## 2. Materials and Methods

This study involved a review of peer-reviewed scientific literature focusing on atmospheric carbon dioxide removal via enhanced rock weathering (ERW) in soils. A comprehensive search was primarily executed across three prominent electronic databases: Scopus, Web of Science, and Google Scholar. The search strategy employed specific keywords, including “basalt”, “basaltic rocks”, “basalt amendment”, “CO<sub>2</sub> removal”,

“enhanced weathering”, and “carbonation”, among other variations. Titles and abstracts were rigorously screened for thematic relevance, providing a robust foundation for analyzing the current state of the art.

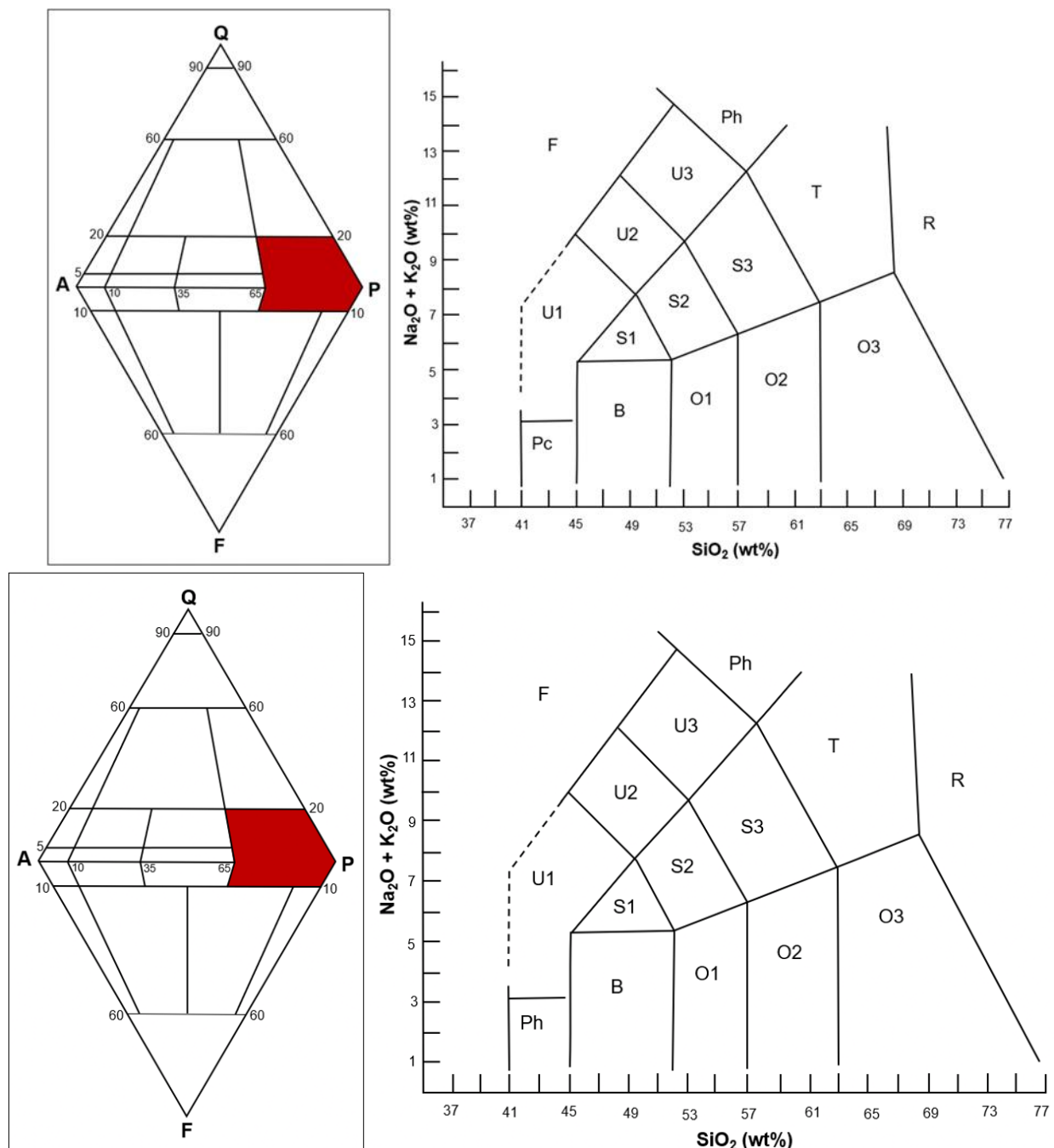
Quantitative analysis of the selected literature revealed that the largest thematic shares were dedicated to enhanced weathering (37%,  $n = 28$ ) and mineral carbonation (36%,  $n = 27$ ). Conversely, geological CO<sub>2</sub> storage (11%,  $n = 8$ ), general basalt characterization (8%,  $n = 6$ ), and other topics (e.g., climate change) (8%,  $n = 6$ ) were less represented. Regarding the temporal distribution, 25% of the references were published between 2022 and 2026 ( $n = 19$ ), 28% between 2017 and 2021 ( $n = 21$ ), 8% between 2012 and 2016 ( $n = 6$ ), and 12% between 2007 and 2011 ( $n = 9$ ), while 27% of the cited works predate 2007 ( $n = 20$ ).

### 3. Basalt: Its Nature

Basalts are aphanitic (fine-grained,  $<1$  mm) mafic volcanic igneous rocks with a basic composition (Figure 2). They are primarily composed of calcic plagioclase, pyroxene (generally augite), and olivine, and to a lesser extent, hornblende, biotite, orthopyroxene, and feldspathoids, with quartz being rare in their composition. Compositional variations exist depending on factors such as their provenance, the type of volcanic activity involved, and the geological evolution of the region [39–41]. According to the Streckisen or QAFP diagram [42], basalt occupies the same field as andesite but is clearly distinguished by its higher color index (generally  $>35$ ) (Figure 3).



**Figure 2.** Basalt outcrop with columnar jointing (Santa Brígida, Gran Canaria, Spain; 28°02′06″ N, 12°30′31″ W).



**Figure 3.** (Left) Streckeisen diagram (QAPF) indicating the position of basalt [42]; Q = Quartz, A = Alkali feldspar, F = Feldspathoids (foids), P = Plagioclase. (Right) TAS (Total Alkali-Silica) diagram for the classification of basalts [43,44]; B = Basalt, O1 = Basaltic andesite, O2 = Andesite, O3 = Dacite, R = Rhyolite, T = Trachyte or Trachydacite, Ph = Phonolite, S1 = Trachybasalt, S2 = Basaltic trachyandesite, S3 = Trachyandesite, Pc = Picrobasalt, U1 = Basanite or Tephrite, U2 = Phonotephrite, U3 = Tephri-phonolite, F = Foidite (melilitites also plot in this area but they differ based on other chemical criteria).

Chemically, basalt contains a series of highly relevant major elements: silicon (Si), oxygen (O), aluminium (Al), iron (Fe), magnesium (Mg), calcium (Ca), sodium (Na), and potassium (K). Specifically, basalt contains between 45% and 53% silica ( $\text{SiO}_2$ ), is enriched in Fe, Mg, and Ca, and exhibits low Na and K contents. Based on silica content, a distinction is made between tholeiitic basalts (silica-saturated to oversaturated) and alkali basalts, which are silica-undersaturated (Figure 4).



**Figure 4.** Basalt powder used in the ‘Smart Green Minerals’ project, located in Ávila, Spain.

However, basalt also contains a suite of trace elements that play a significant role in its geochemical composition. This includes chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), cobalt (Co), phosphorus (P), manganese (Mn), and strontium (Sr), along with many other trace elements present in even smaller quantities. Chromium, a relatively unreactive element, can form chromate or dichromate compounds in oxidizing environments. Meanwhile, copper may form copper oxides or hydroxides under similar conditions. The geochemical composition of basalt is crucial for various applications, particularly regarding the effectiveness of CO<sub>2</sub> sequestration (Figure 4).

#### 4. The Alteration of Basalt

Basalt, like other rocks, undergoes weathering via water-rock interactions [45]. According to the last author, due to their high reactivity, basalts are among the most readily weathered rocks on Earth. As a mafic rock enriched in Fe, Ca, and Mg, basalt exhibits a high mineral trapping potential for converting CO<sub>2</sub> into stable solid carbonates [37,46]. Consequently, during basalt dissolution, divalent cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, and Fe<sup>2+</sup>) are released, reacting with dissolved inorganic carbon to precipitate carbonate minerals. Basaltic materials are considered promising feedstocks because their silicate mineralogy provides the alkaline earth metals essential for solid carbonate formation [26,47,48].

As previously noted, the primary mineral phases in basalt include olivine, pyroxene, plagioclase, and volcanic glass [49]. However, the nature of basaltic materials is not uniform; basaltic glass has been found to dissolve significantly faster (up to 10 times) than its crystalline counterparts. According to Holdren and Berner [50], glass dissolution rates can be up to 100 times higher than those of pure albite at 25 °C and neutral pH. Furthermore, some authors identified Fe, Al, and Ti as the least mobile elements during basalt weathering [51,52]. Minerals with higher reactivity exhibit a greater capacity for CO<sub>2</sub> sequestration, thus enhancing the formation of stable carbonate compounds [53]. In this context, specific surface area plays a pivotal role, although intrinsic reactivity is also governed by mineral composition and crystalline structure. Numerous studies have characterized the dissolution mechanisms of divalent metal-bearing silicates, such as olivine [54–56], pyroxene [57], and plagioclase [32,58,59], as well as volcanic glass [29].

Alteration products result from the breakdown of primary mineral structures through hydrolysis, leaching, and redox processes, forming a continuous developmental sequence from primary minerals to highly weathered products. Chemical trends during

the formation of weathering rinds include significant losses of base cations (Ca, Mg, Na, and K), a minor depletion of SiO<sub>2</sub>, the relative enrichment of sesquioxides, iron oxidation, and water incorporation. These trends can be validated using various weathering indices based on molar ratios.

## 5. Enhanced Weathering: Importance of This Process

Currently, multiple deployment pathways are being explored that differ in weathering rates, costs, scalability, and environmental risks. A significant line of recent research, possessing both scientific and practical importance, is Enhanced Rock Weathering (ERW) or Enhanced Weathering (EW). This technique involves applying pulverized silicate rock to the soil to sequester atmospheric CO<sub>2</sub>, subsequently storing it as calcium carbonate or bicarbonate within the soil matrix (Figure 5).



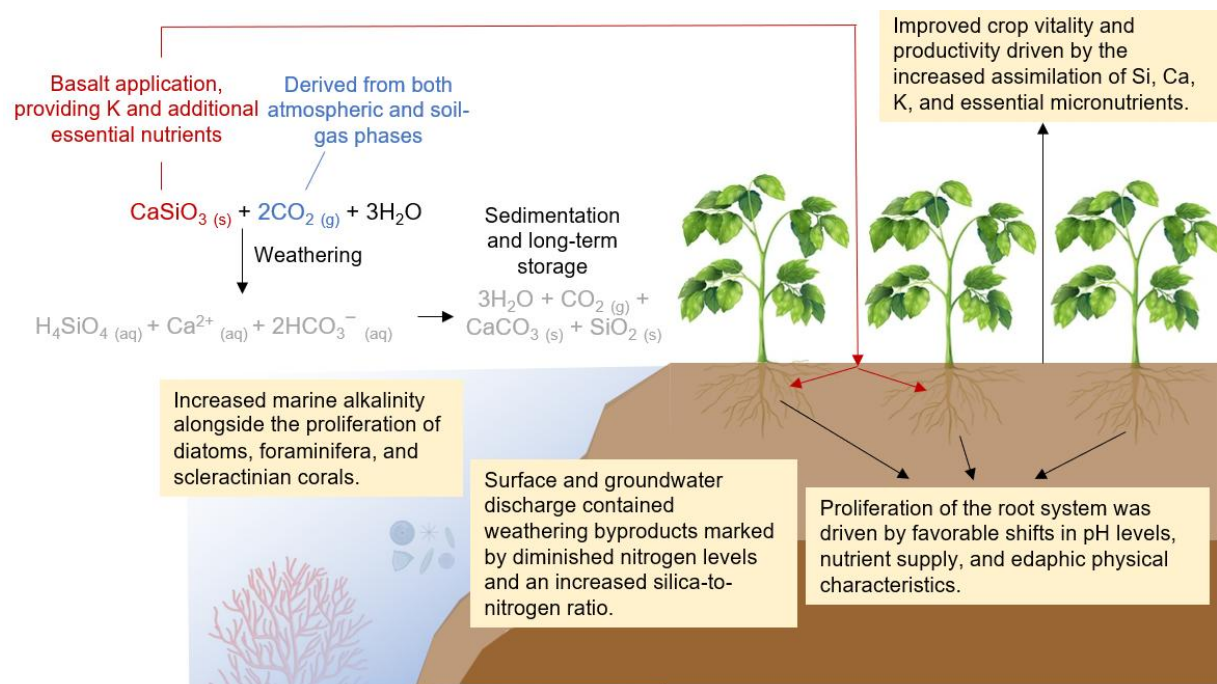
**Figure 5.** Basalt dust was applied to turfgrass soils in landscaped areas as part of the ‘Smart Green Minerals’ project (Ávila, Spain).

Undoubtedly, ERW currently serves as an exploratory method for direct atmospheric CO<sub>2</sub> removal, thereby contributing to the mitigation of climate changes. This is supported by an extensive body of literature [7,12,26,60,61]. Specifically, McGrail et al. [26] demonstrated the potential for carbon dioxide sequestration in flood basalts through experimental evidence, confirming the relatively rapid chemical reaction between CO<sub>2</sub>-saturated pore water and basalt to form stable carbonate minerals. Furthermore, while Figueroa et al. [62] examine the current developmental state of CO<sub>2</sub> capture technologies, Kelland et al. [35] emphasize that the efficacy of basalt-based ERW and its potential agricultural co-benefits necessitate thorough field and experimental evaluation. Consequently, Vicca et al. [3] underscore the imperative of prioritizing these processes within the agenda of this emerging research field.

Fundamentally, this process involves the amendment of soils with crushed rocks, such as basalt, which are characterized by high concentrations of calcium (Ca) and magnesium (Mg) silicate minerals. These minerals undergo rapid chemical weathering reactions [36,63]. The critical mechanism of this approach lies in the sequestration of atmospheric CO<sub>2</sub> within the soil profile, where it is stabilized as calcium carbonate [25,64].

Numerous authors contend that EW, when applied across diverse terrestrial systems—including forests, coastal areas, croplands, and grasslands—serves as an effective mechanism for carbon sequestration and, consequently, contributes to mitigating the effects of climate changes [7,60,65] (Figure 6). Additionally, EW has the capacity to improve soil and crop health by enhancing edaphic nutrient availability and water-holding capacity. This, in turn, results in increased agronomic yields and economic returns [7].

The literature reviewed presents varying data regarding application rates. In large-scale intensive agricultural lands, quantities typically range between 40 and 100  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ , with 50  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  being the most frequently cited figure [5,6,10,35,38]. Anecdotal evidence from practitioners suggests that significantly lower rates (1.5–6  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ ) are recommended for small-scale gardens. The application and distribution of basalt dust may be performed manually or via mechanized spreaders, although the latter may encounter operational difficulties depending on the physical state of the product. Alternative methods include mixing seeds with basalt powder prior to sowing or, for saplings, applying a root dip composed of a slurry of basalt, well-decomposed manure, clay soil, and water.



**Figure 6.** Summary of the potential impacts of basalt dust soil amendments. The weathering of silicate rocks facilitates the release of essential nutrients, thereby enhancing edaphic conditions and bolstering crop productivity. Furthermore, this process yields alkaline leachates that promote the export of dissolved inorganic carbon (DIC) to marine environments (modified from [7]).

Regarding the carbon sequestration potential of basalt dust amendments across various experimental scales, Strefler et al. [66] estimated that global cropland application could remove up to  $4.9 \times 10^9 \text{ Mg CO}_2\cdot\text{yr}^{-1}$  using basalt, and  $95 \times 10^9 \text{ Mg CO}_2\cdot\text{yr}^{-1}$  for dunite. In a laboratory-based assessment, Vicca et al. [3] reported a broader global inorganic carbon sequestration range for enhanced weathering (EW) between  $0.5 \times 10^9$  and  $5.3 \times 10^9 \text{ Mg CO}_2\cdot\text{yr}^{-1}$ . At the field scale, Kelland et al. [35] observed  $\text{CO}_2$  sequestration rates of 2 to 4  $\text{Mg CO}_2\cdot\text{ha}^{-1}$  within one to five years following a 100  $\text{Mg CO}_2\cdot\text{ha}^{-1}$  basalt application in a *Sorghum bicolor* cropland in the UK. Conversely, another UK-based field study utilizing the same application rate (100  $\text{Mg}\cdot\text{ha}^{-1}$ ) reported a significantly lower uptake of 0.0102  $\text{Mg CO}_2\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  [67]. Finally, mesocosm experiments involving *Solanum tuberosum* amended with 50  $\text{Mg}\cdot\text{ha}^{-1}$  of basalt yielded 1.83 and 4.48  $\text{Mg CO}_2\cdot\text{ha}^{-1}$  after one and five years, respectively [5].

Factors such as climatic conditions, microbial activity, and soil type significantly influence the process. For instance, soils with distinct compositions create markedly different weathering environments. In acidic soils, such as Podzols or Ferralsols, the elevated proton concentration accelerates mineral dissolution. Conversely, Calcisols favor carbonate precipitation, and basalt dissolution within these soils can be significantly slower.

Regarding soil texture, sandy soils exhibit high permeability, leading to shortened water residence times. In terms of climatic variables, chemical weathering generally intensifies with increasing temperature, which enhances both reaction kinetics and microbial activity. Consequently, colder regions are characterized by lower dissolution rates.

Despite its promise as a carbon dioxide removal strategy, EW faces significant implementation hurdles that necessitate urgent, audited field-scale evaluations to verify CO<sub>2</sub> sequestration efficacy alongside comprehensive environmental monitoring [7] (Table 1). Current research gaps include a critical lack of empirical data regarding potential unforeseen side effects and long-term field performance [8]. Furthermore, the interplay between mineral grain size and dissolution kinetics remains a fundamental constraint, as these parameters dictate the theoretical and practical deployment potential of the technology [66]. While scientific verification and robust field trials require substantial advancement [28], recent studies have begun addressing these needs; for instance, Buckingham et al. [67] provided direct insights into basalt dissolution rates and soil solution chemistry following high-application rates (100 Mg·ha<sup>-1</sup>) in temperate soils. Consequently, transitioning from theoretical models to standardized, evidence-based field applications remain the primary challenge for the sustainable scaling of EW.

**Table 1.** Research and development needs, categorized by approach and objective, for assessing the viability and effectiveness of enhanced weathering for CO<sub>2</sub> capture via the application of silicate rocks to agricultural soils (modified from [7]).

| Approach                                                                                                                                                                                                                                                                                                                                 | Goal                                                                                                                                        |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Sites encompassing diverse crops and major soil types within global production areas, equipped with eddy-covariance systems to monitor year-round GHG emissions, alongside instrumented field drains for measuring drainage water chemistry and flux, thereby enabling comprehensive mass balances and environmental impact assessments. | Evaluating carbon sequestration, GHG fluxes, and yield optimization to minimize fertilizer inputs and preserve P-reserves.                  |
| Field crop trials involving diverse primary silicate sources, ideally conducted in conjunction with the aforementioned approach.                                                                                                                                                                                                         | Benchmarking sequestration potential of diverse silicate materials (e.g., basalt, melilitite or dunite).                                    |
| Controlled environment tests and replicated field trials regarding the anticipated benefits of silicate application on crop resistance to pests and diseases.                                                                                                                                                                            | Determine translational opportunities for enhancing crop protection and reducing pesticide usage, along with their associated costs.        |
| Genetic selection for high-weathering crops through a combination of enhancing weathering-promoting root exudates and the recruitment of, or association with, beneficial soil microorganisms.                                                                                                                                           | Genetic screening for enhanced weathering capacity and optimized silicic acid release in crop varieties.                                    |
| Genetic screening for Si-induced resistance: Coupling uptake efficiency with jasmonic acid-responsive immune signaling.                                                                                                                                                                                                                  | Elucidating the genetic drivers of Si transport, structural cell wall defense, and systemic immune priming for resilient variety selection. |
| Assessment of farm capacity for silicate storage and application, integrated with current agronomic expertise in liming and silicate-rich slag management.                                                                                                                                                                               | Evaluate the practical feasibility of large-scale cropland deployment.                                                                      |
| Life-cycle economic and energy analysis of silicate processing and spreading, including a cost–benefit comparison with and without carbon credits.                                                                                                                                                                                       | Quantify deployment costs and energy penalties across various scales.                                                                       |
| GIS-based land-use assessment to identify the most economically and environmentally viable areas for silicate application.                                                                                                                                                                                                               | Optimize regional cost–benefit ratios for enhanced weathering.                                                                              |
| Integrate all components into a full-system model—from biogeochemistry to crop yields—compatible with Earth system models.                                                                                                                                                                                                               | Develop realistic simulations to assess Earth system responses to enhanced weathering.                                                      |
| Assess public perceptions of enhanced weathering as a climate mitigation strategy.                                                                                                                                                                                                                                                       | Analyze the ethical and moral drivers of enhanced weathering risk perceptions.                                                              |

Although a quantitative economic evaluation falls outside the scope and specific objectives of this review, economic viability remains a critical factor in assessing the application potential of this CO<sub>2</sub> removal strategy. Costs are highly case-specific, depending on

factors such as the availability and quality of silicate minerals, the energy required for crushing and milling, transport distances, field application logistics, and CO<sub>2</sub> removal monitoring and verification costs. Consequently, cost-effectiveness can vary considerably across regions, crop types, application rates, and land uses. Future studies should therefore integrate techno-economic assessments and life-cycle analyses to determine the net climate benefit of this technology.

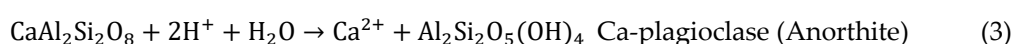
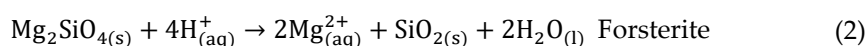
## 6. The Chemical Process: Mineral Carbonation and Its Connection with Basalt Alteration

Among the most widely employed carbon storage techniques is the carbonation of basaltic rocks resulting from their interaction with CO<sub>2</sub> [1,7]. Consequently, mineral carbonation processes have remained closely linked to basalt geochemistry [68]. In summary, research on mineral CO<sub>2</sub> storage in basaltic formations is based on the fact that these rocks—rich in divalent cations such as Ca<sup>2+</sup>, Mg<sup>2+</sup>, and Fe<sup>2+</sup>—undergo accelerated weathering upon contact with CO<sub>2</sub>. The release of these elemental constituents leads to the precipitation of solid carbonate minerals, such as calcite (CaCO<sub>3</sub>), magnesite (MgCO<sub>3</sub>), and siderite (FeCO<sub>3</sub>). This mechanism thus enables long-term CO<sub>2</sub> sequestration [30–32]. As previously discussed, this same geochemical pathway can be applied to soils through the distribution of pulverized basalt.

Carbonation is a reaction initiated by the dissolution of CO<sub>2</sub> in water, leading to the formation of carbonic acid (H<sub>2</sub>CO<sub>3</sub>). This acid subsequently reacts with minerals, leaching metallic cations (e.g., Mg<sup>2+</sup>, Ca<sup>2+</sup>, Fe<sup>2+</sup>) and generating stable carbonate minerals, such as magnesium carbonate, calcium carbonate, and iron carbonate [49]. Mineral reactivity plays a pivotal role in CO<sub>2</sub> carbonation, as highly reactive minerals accelerate the carbonation rate, thereby facilitating the capture and conversion of CO<sub>2</sub> into stable carbonate compounds [17,53,69–71].

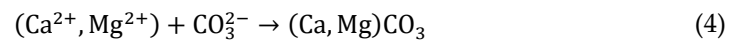
Therefore, the mineral carbonation process is initiated by the interaction of dissolved CO<sub>2</sub> with rocks, particularly those of mafic or ultramafic composition. As CO<sub>2</sub> dissolves in water, it forms carbonic acid (H<sub>2</sub>CO<sub>3</sub>), which promotes the weathering of silicate minerals. Indeed, this aqueous solution exhibits an acidic nature—typically with a pH ranging from 3 to 5—due to the formation of carbonic acid upon contact between CO<sub>2</sub> and water. This pH range is influenced by the partial pressure of CO<sub>2</sub> (pCO<sub>2</sub>), temperature, and the initial chemical composition of the water.

Following this stage, as the acidic fluid interacts with the rock and its constituent minerals, it triggers a weathering process that promotes the dissolution of the silicate minerals within the host rock. The process begins with the gradual leaching of cations, as their bond energies are the weakest. In the case of basalt (the ideal substrate), exothermic chemical reactions occur, originating from structural minerals such as pyroxene, which tend to undergo progressive disintegration through a reaction of the following type:



As observed in the dissolution reactions of forsterite and plagioclase, the release of divalent metallic cations triggers an increase in the solution pH, ultimately leading to carbonate precipitation. This demonstrates that the initial mineralization of CO<sub>2</sub> consumes protons, thereby neutralizing the water charged with the acidic gas (carbonic acid). Crucially, as a result of this preceding reaction, cations such as Ca<sup>2+</sup>, Mg<sup>2+</sup>, and Fe<sup>2+</sup> are liberated; these ions then react with the carbonate (CO<sub>3</sub><sup>2-</sup>) and/or bicarbonate (HCO<sub>3</sub><sup>-</sup>) anions

present in the solution to form stable carbonate minerals. Consequently, the resulting bi-carbonate and carbonate anions either precipitate as calcium and/or magnesium carbonates ( $\text{CaCO}_3$ ,  $\text{MgCO}_3$ ) or are leached into the soil profile, contributing to the mitigation of soil acidification:



Should these ions reach the sea, they also contribute to mitigating the acidification of marine and oceanic environments [61]. This explains the formation of calcite ( $\text{CaCO}_3$ ) and/or aragonite, a process that requires an increase in the solution pH to induce carbonate precipitation.

Therefore, the application of crushed rock containing fast-reacting Ca-Mg silicate minerals to soils—whether agricultural or otherwise—can sequester  $\text{CO}_2$  while simultaneously enhancing edaphic quality and promoting plant development. This improvement stems from the release of essential nutrients, such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{K}^+$ , during weathering, the availability of which depends on the specific rock type employed [7,63]. While most research on Enhanced Weathering (EW) has focused on olivine, particularly forsterite ( $\text{Mg}_2\text{SiO}_4$ ), due to its high weathering rates and  $\text{CO}_2$  drawdown capacity [61], its dissolution also releases nickel cations ( $\text{Ni}^{2+}$ ). Specifically, Te Pas et al. [72] compared the EW potential of olivine, basalt, and wollastonite ( $\text{CaSiO}_3$ ), along with anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ) and albite ( $\text{NaAlSi}_3\text{O}_8$ ). Although all substrates exhibited high  $\text{CO}_2$  capture, elevated Ni concentrations were detected in the leachate from olivine. Consequently, there is a growing shift toward basalt, not only due to its lower Ni content but also because of its superior nutritional profile compared to minerals like olivine [7] and wollastonite [63].

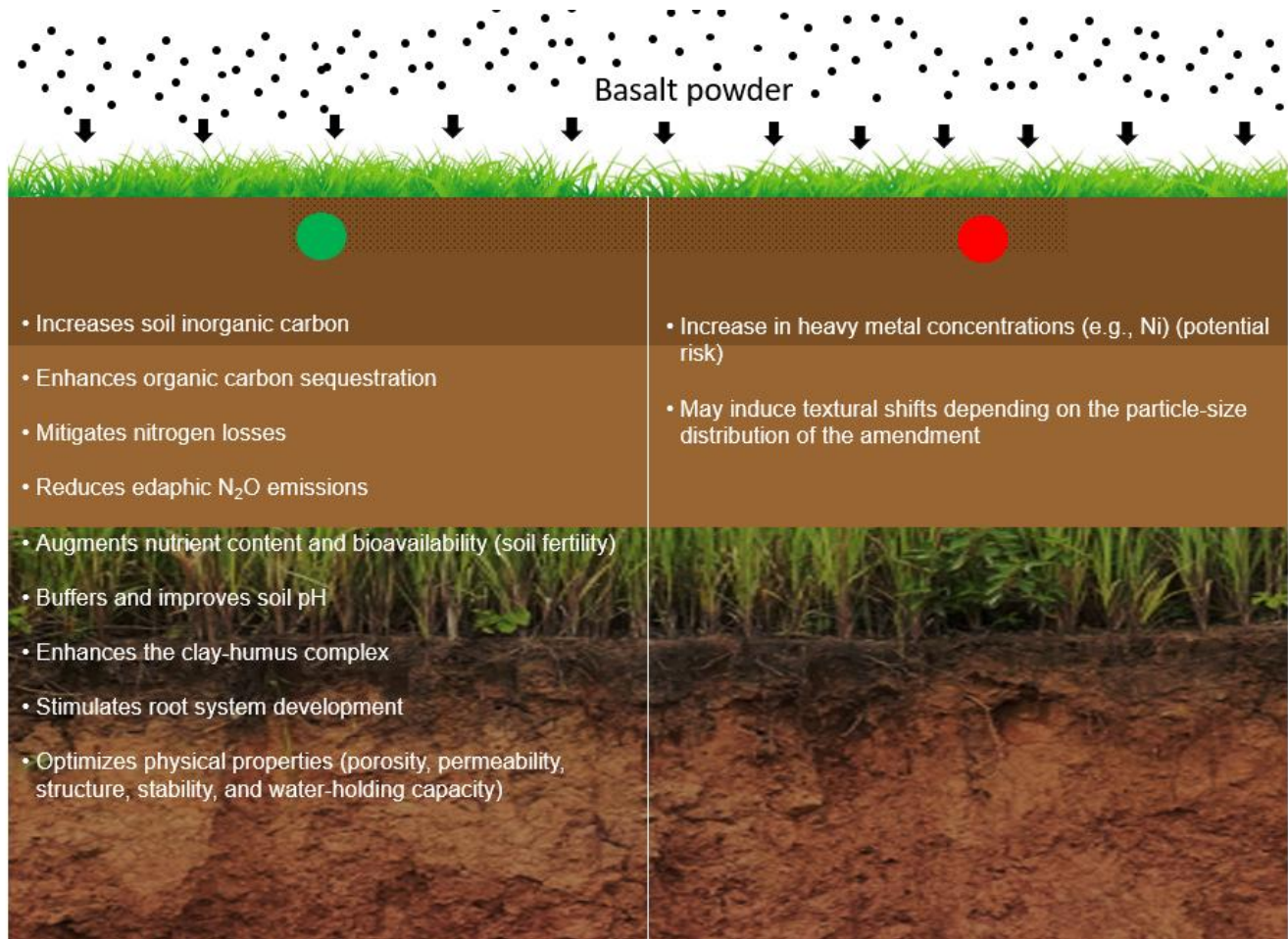
## 7. Additional Benefits of Basalt Amendment

Basalt is a rock historically used in construction and paving, an industry that generates rock dust as a significant byproduct. Repurposing this material for agriculture transforms a potential industrial waste into a high-value resource.

The primary objective of basalt amendment, as previously discussed, is the capture and soil-based sequestration of atmospheric  $\text{CO}_2$ , with the consequent benefit of climate change mitigation [7]. This is complemented by other environmental benefits, such as the reduction in ocean acidification [73], increased agricultural and livestock productivity [9], and the enhancement of soil health and quality [74]. Figure 7 summarizes the primary co-benefits and risks associated with basalt dust amendment on soil properties. Basalt dust acts as a fundamental soil regenerator, contributing directly to the restoration of degraded soils while improving their long-term health and structure [7,9]. Beyond the direct provision of nutrients [8,74], it plays a critical role in the synthesis of the clay-humus complex [6]. This complex is responsible for nutrient availability through cation exchange capacity (CEC), long-term element storage, and the improvement of soil structure and stability (promoting aggregate formation). Consequently, it enhances physical and hydrological properties such as porosity, permeability, and water-holding capacity. Furthermore, basalt dust increases the potential soil organic carbon storage capacity within the ecosystem [8,74], elevates pH levels [72], and reduces nitrogen losses [5].

As a result of soil improvement, basalt dust amendments increase agricultural and livestock productivity. This practice fosters sustainable agriculture, the reduction in agrochemicals (by decreasing dependency on synthetic fertilizers and chemicals), and land sparing; by improving the quality and yield of existing lands, it contributes to the conservation of other ecosystems and their biodiversity [7]. Moreover, it could contribute to combating malnutrition and hunger in regions where agricultural and livestock production is hindered by surface erosion and nutrient depletion [9]. Various studies

demonstrate an increase in net primary productivity (NPP) of crops [10] and improved grassland productivity [6].



**Figure 7.** Synthesis of the primary co-benefits and risks of basalt amendment on soil properties.

However, the literature reports a certain risk of heavy metal contamination. In some experiments involving basalt dust, Ni levels increased (from 57 mg·kg<sup>−1</sup> in the control to 80 mg·kg<sup>−1</sup> with the basalt amendment) but remained below environmental quality standards, and the concentrations of this element in leachates and plant tissues did not increase [5]. In other cases [72], neither the Ni concentrations in the leachates (0.10 mg·kg<sup>−1</sup>) nor in the soil (0.74–2.12 mg·kg<sup>−1</sup>) exceeded regulatory thresholds (50 mg·kg<sup>−1</sup>) [75]. This, however, does not diminish the importance of monitoring the leaching of Ni and other heavy metals, for which no data have been found in trials involving basalt amendments.

## 8. Conclusions

This review article aims to analyze enhanced weathering utilizing basaltic rocks dust as an atmospheric CO<sub>2</sub> removal (CDR) technique, with particular emphasis on the underlying geochemical processes, application methods, experimental results from diverse studies, and associated soil benefits. In this regard, basalt's fine-grained aphanitic texture and mafic composition, rich in Ca, Mg, and Fe cations, facilitate rapid dissolution and high reactivity in enhanced weathering compared to unground rock. The alteration process involves the breakdown of primary silicate minerals (plagioclase, pyroxene, and olivine), releasing these cations to react with CO<sub>2</sub> and form stable carbonates.

The overarching significance of EW lies in its dual role as a high-potential CDR strategy and a driver of agricultural improvement. By stabilizing atmospheric CO<sub>2</sub> as solid

carbonates or dissolved bicarbonates, EW mitigates global warming while simultaneously enhancing soil health, nutrient availability, and crop yields. Consequently, it represents a multifaceted solution for climate stabilization and sustainable food security. However, given the remaining gaps regarding the nutrient release rates of basalt dust application compared to conventional fertilizers, and considering that modern agriculture demands high productivity within limited time and land areas, future studies are highly necessary. Such research should compare its use across different types of agricultural applications, gardens, turfgrass, or forestry lands, alongside leaching trials under varying land uses, topographies, and soil types.

Mineral carbonation is the precipitation of atmospheric CO<sub>2</sub> into stable solid carbonates like calcite and magnesite. This process is linked to basalt alteration because the rock's dissolution releases the necessary divalent cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, Fe<sup>2+</sup>) that react with bicarbonate anions to permanently sequester carbon. Beyond nutrient replenishment of over 70 elements, basalt application restores “background fertility” and aids the synthesis of the clay-humus complex, which improves soil structure, water-holding capacity, and cation exchange. Furthermore, it enhances biological fertility by bolstering plant resistance to biotic and abiotic stressors and acts as a sustainable soil regenerator by repurposing industrial byproducts.

Despite its potential, enhanced weathering still faces significant implementation gaps, primarily regarding the scarcity of audited, field-scale assessments to verify CO<sub>2</sub> sequestration efficacy. Benefits such as the reduction in ocean acidification and the increase in agricultural and livestock productivity are considered relevant, in addition to the enhancement of soil health and quality, particularly the provision of nutrients. However, critical uncertainties remain concerning the complex interplay between grain size distributions and actual mineral dissolution rates under varying pedological conditions. Furthermore, there is an urgent need to address unknown environmental side effects and provide long-term monitoring of soil solution chemistry to bridge the current lack of empirical data. Future research must prioritize standardized scientific verification and direct field trials—such as high-application basalt amendments—to accurately quantify weathering kinetics and the sustainable development of this carbon removal technology.

In conclusion, enhanced weathering represents a highly promising technique for atmospheric CO<sub>2</sub> removal in the mitigation of climate change. However, its implementation still necessitates further experimental evidence across diverse environments, standardized protocols, and the resolution of ongoing controversies, such as the net climate benefit after life-cycle emissions or agricultural co-benefits versus risks, alongside a comprehensive economic analysis.

**Author Contributions:** Conceptualization, J.M.-M. and R.J.-B.; methodology, H.M.-V., J.M.-M., R.J.-B. and M.d.M.-M.; validation, H.M.-V., J.M.-M. and R.J.-B.; formal analysis, H.M.-V., J.M.-M. and R.J.-B.; investigation, H.M.-V., J.M.-M. and R.J.-B.; resources, J.M.-M.; data curation, H.M.-V., J.M.-M. and R.J.-B.; writing—original draft preparation, H.M.-V., J.M.-M., R.J.-B. and M.d.M.-M.; writing—review and editing, H.M.-V., J.M.-M., R.J.-B. and M.d.M.-M.; visualization, J.M.-M. and R.J.-B.; supervision, J.M.-M. and R.J.-B.; project administration, J.M.-M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study has been funded by the company LG Electronic España within the Smart Green Minerals project (COL2025\_007).

**Data Availability Statement:** The data and materials will be made available from the corresponding author upon reasonable request.

**Acknowledgments:** The authors would like to thank the company TREMISA and the Ávila City Council for their collaboration within the Smart Green Minerals project.

**Conflicts of Interest:** The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## References

1. Snæbjörnsdóttir, S.Ó.; Sigfússon, B.; Marieni, C.; Goldberg, D.; Gislason, S.R.; Oelkers, E.H. Carbon dioxide storage through mineral carbonation. *Nat. Rev. Earth Environ.* **2020**, *1*, 90–102.
2. United Nations. *Paris Agreement*; United Nations: New York, NY, USA, 2017.
3. Vicca, S.; Goll, D.S.; Hagens, M.; Hartmann, J.; Janssens, I.A.; Neubeck, A.; Peñuelas, J.; Poblador, S.; Rijnders, J.; Sardans, J.; et al. Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes? *Glob. Change Biol.* **2022**, *28*, 711–726.
4. Calabrese, S.; Wild, B.; Bertagni, M.B.; Bourg, I.C.; White, C.; Aburto, F.; Cipolla, G.; Noto, L.V.; Porporato, A. Environmental controls on mineral weathering. *Environ. Sci. Technol.* **2022**, *56*, 15261–15272.
5. Vienne, A.; Poblador, S.; Portillo-Estrada, M.; Hartmann, J.; Ijehon, S.; Wade, P.; Vicca, S. Enhanced weathering using basalt rock powder: carbon sequestration, co-benefits and risks in a mesocosm study with *Solanum tuberosum*. *Front. Clim.* **2022**, *4*, 869456.
6. Reynaert, S.; Vienne, A.; De Boeck, H.J.; D'Hose, T.; Janssens, I.; Nijs, I.; Portillo-Estrada, M.; Verbruggen, E.; Vicca, S.; Poblador, S. Basalt addition improves the performance of young grassland monocultures under more persistent weather featuring longer dry and wet spells. *Agric. For. Meteorol.* **2023**, *340*, 109610.
7. Beerling, D.J.; Leake, J.R.; Long, S.P.; Scholes, J.D.; Ton, J.; Nelson, P.N.; Bird, M.; Kantzas, E.; Taylor, L.L.; Sarkar, B.; et al. Farming with crops and rocks to address global climate, food and soil security. *Nat. Plants* **2018**, *4*, 138–147.
8. Goll, D.S.; Ciais, P.; Amann, T.; Buermann, W.; Chang, J.; Eker, S.; Hartmann, J.; Janssens, I.; Li, W.; Obersteiner, M.; et al. Potential CO<sub>2</sub> removal from enhanced weathering by ecosystem responses to powdered rock. *Nat. Geosci.* **2021**, *14*, 545–549.
9. Janssens, I.A.; Roobroeck, D.; Sardans, J.; Obersteiner, M.; Peñuelas, J.; Richter, A.; Smith, P.; Verbruggen, E.; Vicca, S. Negative erosion and emissions: Land-based CO<sub>2</sub> removal techniques. *Front. Clim.* **2022**, *4*, 928403.
10. Kantola, I.B.; Blanc-Betes, E.; Masters, M.D.; Chang, E.; Marklein, A.; Moore, C.E.; von Haden, A.; Bernacchi, C.J.; Wolf, A.; Epihov, D.Z.; et al. Improved net carbon budgets in the US Midwest through direct measured impacts of enhanced weathering. *Glob. Change Biol.* **2023**, *29*, 7012–7028.
11. IEA. *World Energy Outlook 2017*; OECD: Paris, France, 2017.
12. IPCC. *Global Warming of 1.5 °C*; IPCC: Geneva, Switzerland, 2018.
13. Scharlemann, J.P.W.; Tanner, E.V.J.; Hiederer, R.; Kapos, V. Global soil carbon. *Carbon Manag.* **2014**, *5*, 81–91.
14. Rumpel, C.; Amiraslani, F.; Chenu, C.; Garcia Cardenas, M.; Kaonga, M.; Koutika, L.S.; Ladha, J.; Madari, B.; Shirato, Y.; Smith, P.; et al. The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *Ambio* **2020**, *49*, 350–360.
15. Minasny, B.; Malone, B.P.; McBratney, A.B.; Angers, D.A.; Arrouays, D.; Chambers, A.; Chaplot, V.; Chen, Z.-S.; Cheng, K.; Das, B.S.; et al. Soil carbon 4 per mille. *Geoderma* **2017**, *292*, 59–86.
16. FAO; ITPS. *Recarbonizing Global Soils: A Technical Manual of Recommended Management Practices*; Volume 1: Introduction and Methodology; FAO: Rome, Italy, 2021.
17. Liu, D.; Agarwal, R.; Liu, F.; Yang, S.; Li, Y. CO<sub>2</sub> geological storage in Deccan basalts. *Environ. Sci. Pollut. Res.* **2022**, *29*, 85465–85481.
18. Ali, M.; Yekeen, N.; Alanazi, A.; Keshavarz, A.; Iglaue, S.; Finkbeiner, T.; Hoteit, H. Saudi Arabian basalt/CO<sub>2</sub>/brine wettability: Implications for CO<sub>2</sub> geo-storage. *J. Energy Storage* **2023**, *62*, 106921.
19. Raza, A.; Glatz, G.; Gholami, R.; Mahmoud, M.; Alafnan, S. Carbon mineralization in basalt. *Earth-Sci. Rev.* **2022**, *229*, 104036.
20. Liu, D.; Agarwal, R.; Li, Y.; Yang, S. Reactive transport modeling of mineral carbonation in basalts. *Int. J. Greenh. Gas Control* **2019**, *85*, 109–120.
21. Gadikota, G. Multiphase carbon mineralization for CO<sub>2</sub> separation. *Nat. Rev. Chem.* **2020**, *4*, 78–89.
22. Gadikota, G.; Matter, J.; Kelemen, P.; Park, A.H. Olivine carbonation reactions. *Phys. Chem. Chem. Phys.* **2014**, *16*, 4679–4693.
23. Loring, J.S.; Miller, Q.R.S.; Thompson, C.J.; Schaef, H.T. Experimental studies of mineral reactivity in supercritical CO<sub>2</sub>. In *Science of Carbon Storage in Deep Saline Formations*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 63–88.
24. Gaillardet, J.; Dupré, B.; Louvat, P.; Allègre, C.J. Global silicate weathering and CO<sub>2</sub> consumption. *Chem. Geol.* **1999**, *159*, 3–30.
25. Dessert, C.; Dupré, B.; Gaillardet, J.; François, L.M.; Allègre, C.J. Basalt weathering laws and impact on the global carbon cycle. *Chem. Geol.* **2003**, *202*, 257–273.

26. McGrail, B.P.; Schaef, H.T.; Ho, A.M.; Chien, Y.J.; Dooley, J.J.; Davidson, C.L. Potential for carbon dioxide sequestration in flood basalts. *J. Geophys. Res.* **2006**, *111*, B12201.
27. Anthonsen, K.L.; Aagaard, P.; Bergmo, P.E.S.; Erlström, M.; Fareide, J.I.; Gislason, S.R.; Mortensen, G.M.; Snæbjörnsdóttir, S.Ó. CO<sub>2</sub> storage potential in the Nordic region. *Energy Procedia* **2013**, *37*, 5080–5092.
28. Almaraz, M.; Bingham, N.L.; Holzer, I.O.; Geoghegan, E.K.; Goertzen, H.; Sohng, J.; Houlton, B.Z. Methods for determining the CO<sub>2</sub> removal capacity of enhanced weathering in agronomic settings. *Front. Clim.* **2022**, *4*, 970429.
29. Wolff-Boenisch, D.; Gislason, S.R.; Oelkers, E.H. Silicate dissolution rates and CO<sub>2</sub> consumption. *Geochim. Cosmochim. Acta* **2006**, *70*, 858–870.
30. Gislason, S.R.; Wolff-Boenisch, D.; Stefansson, A.; Oelkers, E.H.; Gunnlaugsson, E.; Sigurdardóttir, H.; Sigfusson, B.; Broecker, W.S.; Matter, J.M.; Stute, M.; et al. Mineral sequestration of carbon dioxide in basalt: A pre-injection overview of the CarbFix project. *Int. J. Greenh. Gas Control* **2010**, *4*, 537–545.
31. Gislason, S.R.; Oelkers, E.H. Mechanism, rates, and consequences of basaltic glass dissolution: II. Experimental study of dissolution rates as a function of pH and temperature. *Geochim. Cosmochim. Acta* **2003**, *67*, 3817–3832.
32. Oelkers, E.H.; Gislason, S.R.; Matter, J. Mineral carbonation of CO<sub>2</sub>. *Elements* **2008**, *4*, 333–337.
33. Gislason, S.R.; Broecker, W.S.; Gunnlaugsson, E.; Snæbjörnsdóttir, S.Ó.; Mesfin, K.G.; Alfredsson, H.A.; Aradóttir, E.S.; Sigfusson, B.; Gunnarsson, I.; Stute, M.; et al. Rapid solubility and mineral storage of CO<sub>2</sub> in basalt. *Energy Procedia* **2014**, *63*, 4561–4574.
34. Schaef, H.T.; McGrail, B.P.; Owen, A.T. Carbonate mineralization of basalts. *Int. J. Greenh. Gas Control* **2010**, *4*, 249–261.
35. Kelland, M.E.; Wade, P.W.; Lewis, A.L.; Taylor, L.L.; Sarkar, B.; Andrews, M.G.; Lomas, M.R.; Cotton, T.E.A.; Kemp, S.J.; James, R.H.; et al. Increased yield and CO<sub>2</sub> sequestration potential with the C4 cereal *Sorghum bicolor* cultivated in basaltic rock dust-amended agricultural soil. *Glob. Change Biol.* **2020**, *26*, 3658–3676.
36. Beerling, D.J.; Kantzas, E.P.; Lomas, M.R.; Wade, P.; Eufrazio, R.M.; Renforth, P.; Sarkar, B.; Andrews, M.G.; James, R.H.; Pearce, C.R.; et al. Potential for large-scale CO<sub>2</sub> removal via enhanced rock weathering with croplands. *Nature* **2020**, *583*, 242–248.
37. Goff, F.; Lackner, K. Carbon dioxide sequestration using ultramafic rocks. *Environ. Geosci.* **1998**, *5*, 89–101.
38. Dupla, X.; Möller, B.; Baveye, P.C.; Grand, S. Trace element accumulation during enhanced weathering. *Eur. J. Soil Sci.* **2023**, *74*, 13343.
39. Ellam, R. Lithospheric thickness as a control on basalt geochemistry. *Geology* **1992**, *20*, 153–156.
40. Rhodes, J.M.; Vollinger, M.J. Composition of basaltic lavas in Hawaii. *Geochem. Geophys. Geosyst.* **2004**, *5*, 3.
41. Doucet, L.S.; Tetley, M.G.; Li, Z.-X.; Liu, Y.; Gamaleldien, H. Geochemical fingerprinting of basalts: A machine learning approach. *Earth-Sci. Rev.* **2022**, *233*, 104192.
42. Streckeisen, A. To each plutonic rock its proper name. *Earth Sci. Rev.* **1976**, *12*, 1–33.
43. Johannsen, A. *A Descriptive Petrography of the Igneous Rocks*; Volume 1: Introduction, Textures, Classifications, and Glossary; University of Chicago Press: Chicago, IL, USA, 1937.
44. Le Maitre, R.W.; Streckeisen, A.; Zanettin, B.; Le Bas, M.J.; Bonin, B.; Bateman, P. *Igneous Rocks: A Classification and Glossary of Terms*; Cambridge University Press: Cambridge, UK, 2002.
45. Gislason, S.R.; Arnórsson, S.; Ármannsson, H. Chemical weathering of basalt in Southwest Iceland: Effects of runoff, rock age, and vegetation. *Am. J. Sci.* **1996**, *296*, 837–907.
46. Matter, J.M.; Kelemen, P.B. Permanent CO<sub>2</sub> storage by mineral carbonation. *Nat. Geosci.* **2009**, *2*, 837–841.
47. Oelkers, E.H.; Schott, J.; Gauthier, J.M. Dissolution mechanism of muscovite. *Geochim. Cosmochim. Acta* **2008**, *72*, 4948–4961.
48. Goldberg, D.S.; Takahashi, T.; Slagle, A.L. Carbon dioxide sequestration in deep-sea basalt. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 9920–9925.
49. Rasool, M.H.; Ahmad, M. Reactivity of basaltic minerals for CO<sub>2</sub> sequestration. *Minerals* **2023**, *13*, 1154.
50. Holdren, G.J.; Berner, R.A. Mechanism of feldspar weathering—I. Experimental studies. *Geochim. Cosmochim. Acta* **1979**, *43*, 1161–1171.
51. Nesbitt, H.W.; Wilson, R.E. Chemical weathering of basalts. *Am. J. Sci.* **1992**, *292*, 740–777.
52. Taylor, A.S.; Lasaga, A.C.; Blum, J.D. Effect of lithology on silicate weathering. In *Geochemistry of the Earth's Surface*; Balkema: Rotterdam, The Netherlands, 1999; pp. 127–128.
53. Yadav, S.; Mehra, A. Ex situ mineral carbonation. *Environ. Sci. Pollut. Res.* **2021**, *28*, 12202–12231.
54. Rosso, J.J.; Rimstidt, J.D. Forsterite dissolution rates. *Geochim. Cosmochim. Acta* **2000**, *64*, 797–811.
55. Golubev, S.V.; Pokrovsky, O.S.; Schott, J. Dissolution kinetics of silicates. *Chem. Geol.* **2005**, *217*, 227–238.
56. Gadikota, G.; Matter, J.; Kelemen, P.; Brady, P.V.; Park, A.-H.A. Elucidating differences in carbon mineralization behaviors of aluminosilicates and magnesium silicates for CO<sub>2</sub> storage. *Fuel* **2020**, *277*, 117900.

57. Brantley, S.L.; Chen, Y. Chemical weathering rates of pyroxenes and amphiboles. In *Chemical Weathering Rates of Silicate Minerals*; White, A.F., Brantley, S.L., Eds.; Walter de Gruyter GmbH: Berlin, Germany, 1995.
58. Metz, V.; Amram, K.; Ganor, J. Stoichiometry of smectite dissolution. *Geochim. Cosmochim. Acta* **2005**, *69*, 1755–1772.
59. Gudbrandsson, S.; Wolff-Boenisch, D.; Gislason, S.R.; Oelkers, E.H. Plagioclase dissolution rates. *Geochim. Cosmochim. Acta* **2014**, *139*, 154–172.
60. Schuiling, R.D.; Krijgsman, P. Enhanced weathering: an effective and cheap tool to sequester CO<sub>2</sub>. *Clim. Change* **2006**, *74*, 349–354.
61. Hartmann, J.; West, A.J.; Renforth, P.; Köhler, P.; De La Rocha, C.L.; Wolf-Gladrow, D.A.; Dürr, H.H.; Scheffran, J. Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.* **2013**, *51*, 113–149.
62. Figueroa, J.; Fout, T.; Plasynski, S.I.; McIlvried, H.; Srivastava, R. Advances in CO<sub>2</sub> capture technology—The U.S. Department of Energy’s Carbon Sequestration Program. *Int. J. Greenh. Gas Control* **2008**, *2*, 9–20.
63. Haque, F.; Santos, R.M.; Chiang, Y.W. Urban farming with enhanced rock weathering as a climate stabilization strategy. *Environ. Sci. Technol.* **2021**, *55*, 13575–13578.
64. Matter, J.M.; Takahashi, T.; Goldberg, D. Experimental evaluation of in situ CO<sub>2</sub>-water-rock reactions during CO<sub>2</sub> injection in basaltic rocks: Implications for geological CO<sub>2</sub> sequestration. *Geochem. Geophys. Geosyst.* **2007**, *8*, Q02001.
65. Meysman, F.J.; Montserrat, F. Negative CO<sub>2</sub> emissions via coastal enhanced weathering. *Biol. Lett.* **2017**, *13*, 20160905.
66. Strefler, J.; Amann, T.; Bauer, N.; Kriegler, E.; Hartmann, J. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environ. Res. Lett.* **2018**, *13*, 034010.
67. Buckingham, F.L.; Henderson, G.M.; Holdship, P.; Renforth, P. Soil core study indicates limited CO<sub>2</sub> removal by enhanced weathering in dry croplands in the UK. *Appl. Geochem.* **2022**, *147*, 105482.
68. Xia, L.; Li, X. Basalt geochemistry and tectonic setting. *Gondwana Res.* **2018**, *65*, 43–67.
69. Kwak, J.H.; Hu, J.Z.; Turcu, R.V.; Rosso, K.M.; Ilton, E.S.; Wang, C.; Sears, J.A.; Engelhard, M.H.; Felmy, A.R.; Hoyt, D.W. Role of H<sub>2</sub>O in carbonation of forsterite in supercritical CO<sub>2</sub>. *Int. J. Greenh. Gas Control* **2011**, *5*, 1081–1092.
70. Wood, C.E.; Qafoku, O.; Loring, J.S.; Chaka, A.M. Role of Fe(II) in olivine carbonation. *Environ. Sci. Technol. Lett.* **2019**, *6*, 592–599.
71. Lu, X.; Carroll, K.J.; Turvey, C.C.; Dipple, G.M. Cation release from ultramafic tailings for carbon capture. *Appl. Geochem.* **2022**, *140*, 105285.
72. Te Pas, E.E.E.M.; Hagens, M.; Comans, R.N.J. Enhanced weathering potential of silicate minerals. *Front. Clim.* **2023**, *4*, 954064.
73. Eufrazio, R.M.; Kantzas, E.P.; Edwards, N.R.; Holden, P.B.; Pollitt, H.; Mercure, J.-F.; Koh, S.C.L.; Beerling, D.J. Environmental and health impacts of atmospheric CO<sub>2</sub> removal by enhanced rock weathering depend on nations’ energy mix. *Commun. Earth Environ.* **2022**, *3*, 106.
74. Yang, P.; Li, J. Research progress on impact of basalt application on farmland soil, crop growth, and carbon sequestration. *Agric. Eng.* **2024**, *14*, 111–120.
75. Tóth, G.; Hermann, T.; Da Silva, M.R.; Montanarella, L. Heavy metals in agricultural soils of the European Union with implications for food safety. *Environ. Int.* **2016**, *88*, 299–309.

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