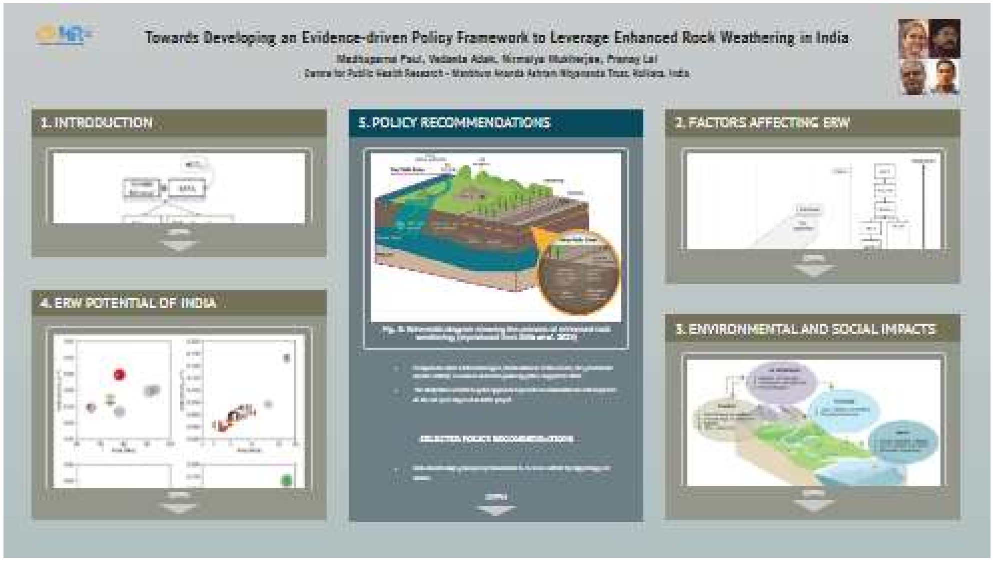
Towards Developing an Evidence-driven Policy Framework to Leverage Enhanced Rock Weathering in India



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PRESENTED AT:

1. INTRODUCTION

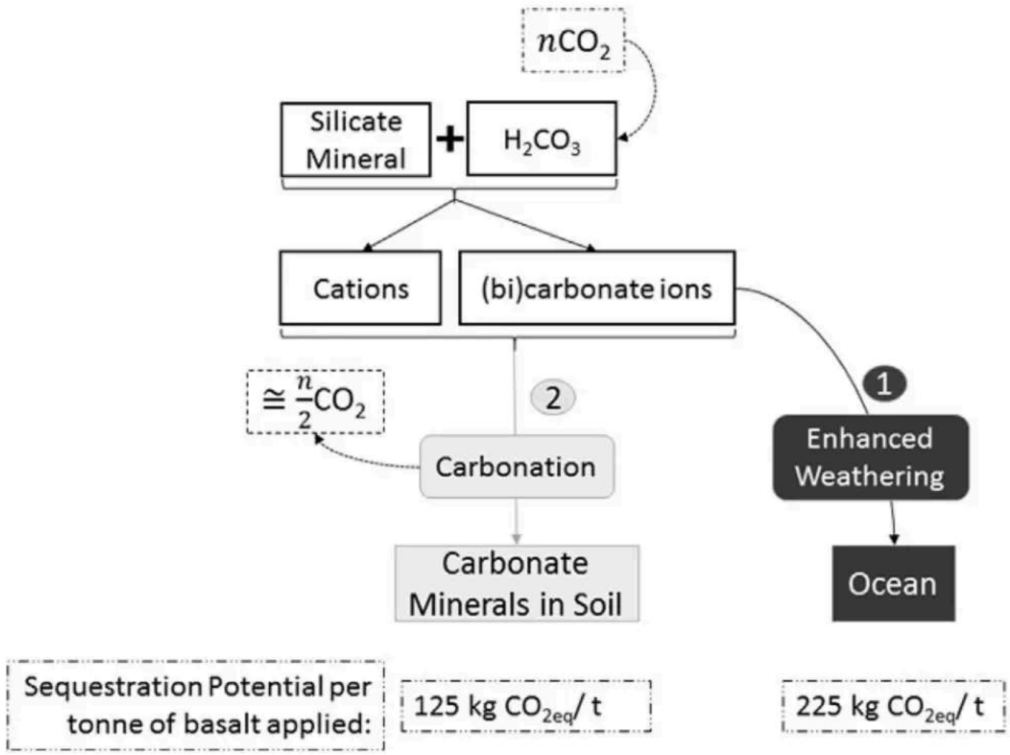


Fig. 1: General overview of the enhanced rock weathering process and the two pathways it can take (reproduced from *Lefebvre et al. 2019*)

- Human-induced emissions of CO_2 and other greenhouse gases over ~150 years have raised global average temperatures by ~1.2°C (WMO, 2020).

- IPCC's Fifth Assessment Report shows 104 out of 116 climate scenarios require carbon dioxide removal (CDR) to meet temperature targets.

- Enhanced Rock Weathering (ERW) is a novel CDR technique with high potential and agricultural co-benefits.

ENHANCED ROCK WEATHERING FUNDAMENTALS:

- Natural rock weathering processes involves mechanical weathering which breaks down the rocks into smaller pieces while chemical weathering results in change in composition (Tarbuck & Lutgens, 2012)
- This natural weathering process removes atmospheric CO_2 via dissolution of silicate or carbonate minerals.
- ERW involves mixing crushed/powdered silicate rocks (which increases the reaction surface area) with soil to fasten the process of carbon capture (Fig. 1) that naturally occurs during rock weathering.

- Land based application of ERW in croplands have the added advantage of increasing agricultural yield and reducing CO_2 emissions related to agriculture (Skov et al. 2024; Beerling et al. 2025).
- Following hydration of CO_2 and silicate dissolution, two pathways are possible
    1. Carbonate mineral formation and precipitation in soil - leads to 50% loss in carbon dioxide back into the atmosphere
    2. Bicarbonate and metal migration from soil - leads to no precipitation of either carbon or cations into the soil

4. ERW POTENTIAL OF INDIA

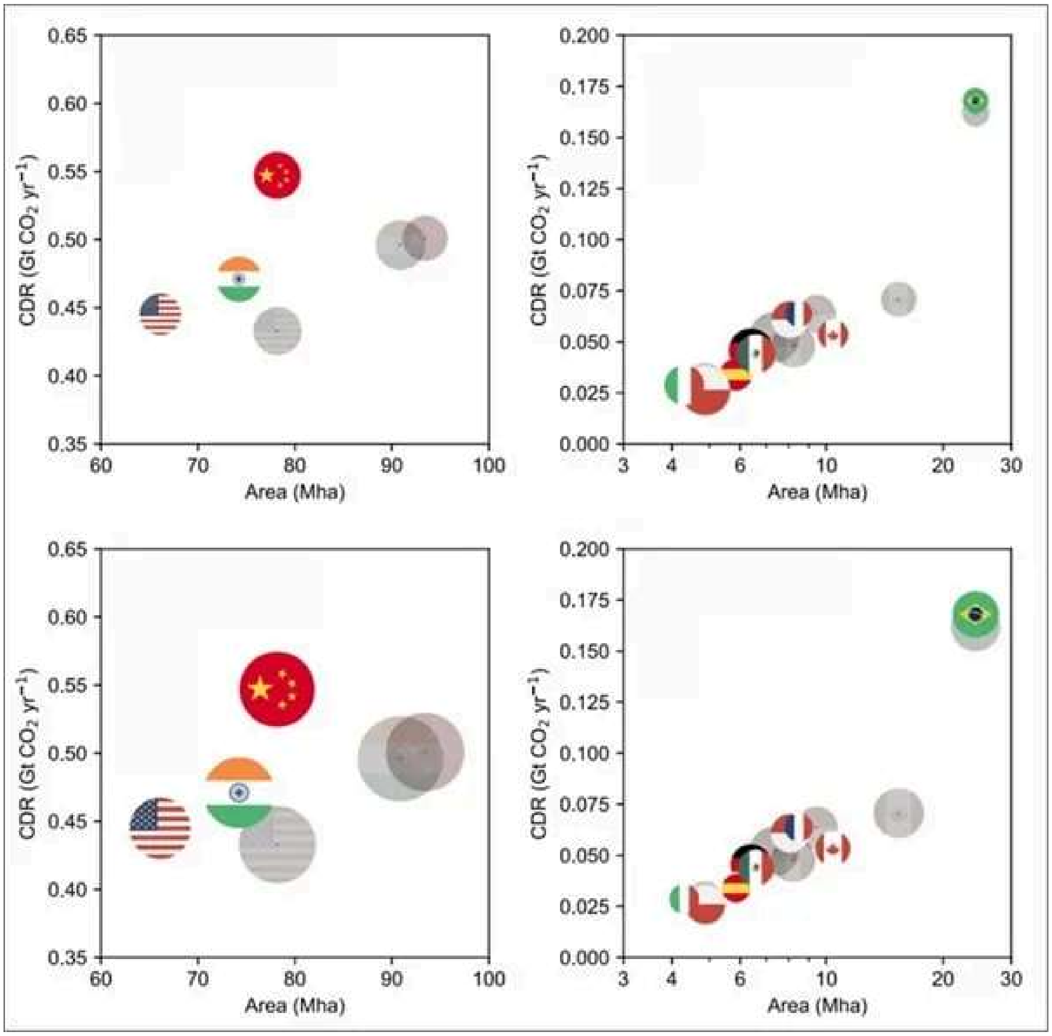


Fig. 4: CDR potential vs. cropland area diagram for different countries. Size of the circles represent the value of sustainability index. Bright flags are business-as-usual scenario and shaded circles are based on energy policy scenarios for 2°C. Top left- Sustainability index of ERW across India, China and USA relative to area of cropland on which ERW is deployed vs CDR potential; Top right - Sustainability index of ERW across 9 other countries (Canada, Mexico, Brazil, etc.) relative to area of cropland on which ERW is deployed vs CDR potential. Bottom left: Area integrated sustainability index for the same countries as in top left image; Bottom right - Area integrated sustainability index for the same countries as in top right image (modified after *Eufrasio et al. 2022*)

- India has one of the largest CDR potentials in the world having extensive rock exposures (including Deccan basalts), tropical climate and huge amount of farmland available for rock dust application (Strefler et al. 2018; Beerling et al. 2020; Eufrasio et al. 2022).
- Depending on the distance from basalt source regions to croplands the rail distance, costs and CO_2 emissions that maybe associated with the nationwide adoption of ERW in India is either lowest or reasonable for most parts of India, compared to many countries across the world (Beerling et al. 2020)
- According to a recent study based on end point effects on resource depletion, ecosystem conditions and human health, India has the second highest potential (Fig. 4) for scalability and long-term sustenance of ERW in the world (Eufrasio et al. 2022).

- This evaluation suggests that India along with some other countries (like Poland, Germany) have the highest probability of reaching resource depletion under current business-as-usual scenarios for ERW.
- In terms of damage to ecosystems most countries show similar trends, including India.
- It is important to note, that in this study India shows the most vulnerability in terms of impact to human health. Therefore, all precautions must be taken to reduce such effects

5. POLICY RECOMMENDATIONS

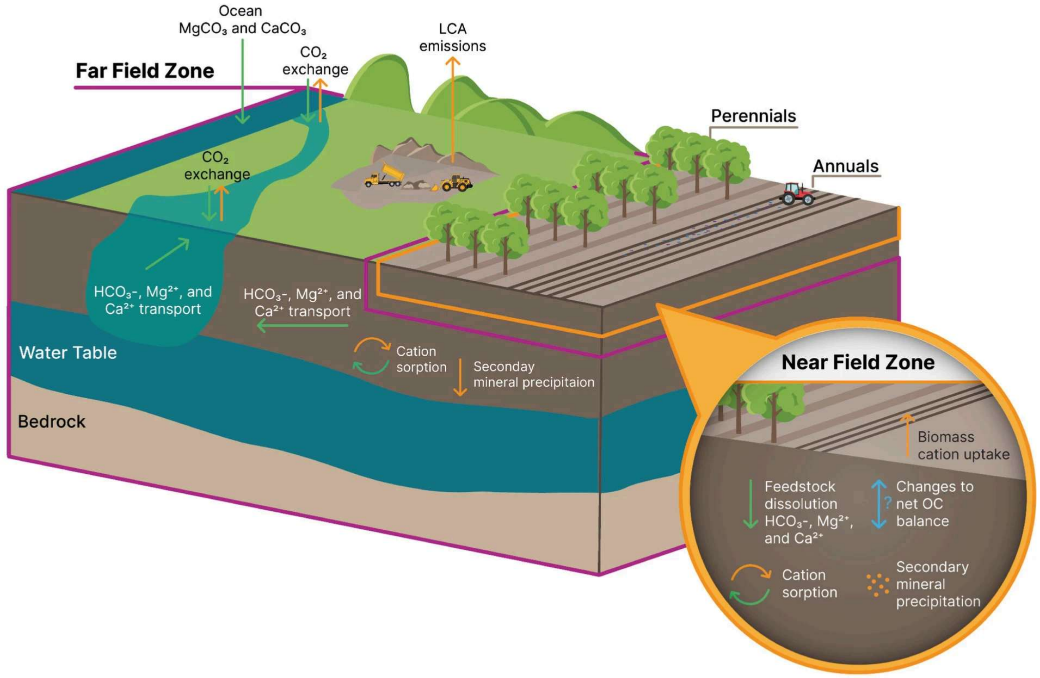


Fig. 5: Schematic diagram showing the process of enhanced rock weathering (reproduced from *Mills et al. 2024*)

- Compared to other CDR technologies, trustworthiness of the science, the government and the industry is a crucial factor for garnering public support for ERW.
- The study takes a cradle to grave approach to provide recommendations with respect to all the life cycle stages of an ERW project.

SELECTED POLICY RECOMMENDATIONS

- India should adapt global policy frameworks to its local contexts by supporting pilot studies.
- Given India's diverse agro-climatic zones, it is essential to generate locally relevant evidence on crop yields, soil chemistry and socio-economic impacts across these regions before considering large-scale deployment.
- The study does not recommend the issuance of new mining leases for quarrying of ERW feedstocks, instead use mine tailings and other overburden for current ERW projects
- Nodal agency should be the Ministry of Mines, with the Geological Survey of India as the lead agency for the measurement, reporting and verification (MRV) of ERW feedstocks
- Leveraging the use of existing geochemical and lithological maps (1:25,000) to select suitable rock

types for ERW.

- Projects should follow processes of environmental clearances from both national and state cells with Environmental Impact Assessment (EIA), along with local consultations.

- Source Rock Testing: Before processing, test ERW feedstock batches for heavy metals (Ni, Cr, Pb, Cd, As, etc.) and other toxins. Reject or limit high-PTE batches.

- Energy Use Tracking: Record electricity/fuel consumption for grinding; prefer renewable energy sources to minimize life-cycle emissions.

- Loading/Unloading Protocols: Prefer mechanized handling; if manual, ensure PPE and labor law compliance.

  Dust Control: Tarpaulin covers on trucks; water sprays during loading/unloading; road watering and wheel-wash stations to prevent dust dispersal.

- Emissions Accounting: Include diesel emissions in LCA; explore route optimization or cleaner vehicles to reduce carbon footprint.

- Farmer/Miner safety: Ensure proper protective and safety gears including masks, gloves and other equipment for the people working with ERW feedstocks.

- Involvement of the Central Ground Water Board to monitor groundwater, stream and river health; and Indian Council of Agricultural Research to monitor soil health and crop yields.

2. FACTORS AFFECTING ERW

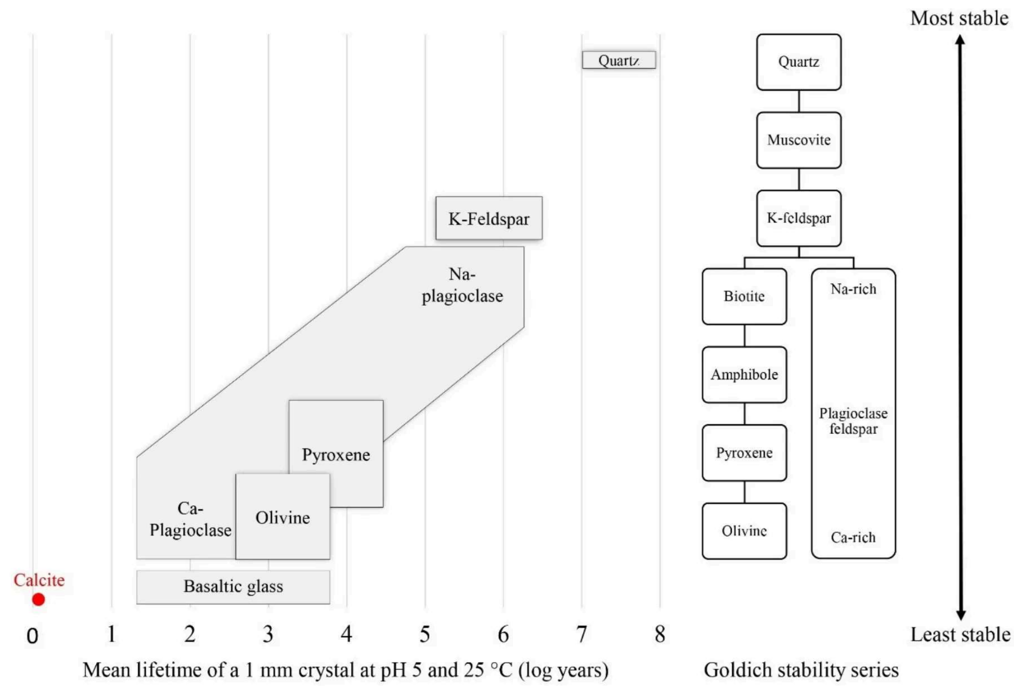


Fig. 2.1: Goldich stability series on the right and mean lifetime (in years) of a 1mm crystal for common minerals in basalt under pH 5 and 25°C on the left (reproduced from *Dupla et al. 2025*).

The rate of weathering of silicate minerals is dependent on a range of factors:

- **Mineralogy -** The minerals present in a rock used in ERW not only controls its CO_2 drawdown potential but also its rate of weathering. While some minerals like forsterite are fast dissolving, others like K-feldspar are orders of magnitude slower (Fig. 2.1).
- **Grain Size -** Decrease in grain size increases the reaction surface area for any specific volume of grains. Both experimental and modelling studies suggest that reaction kinetics for the silicate dissolution reactions increase with decrease in grain size (Fig. 2.2).

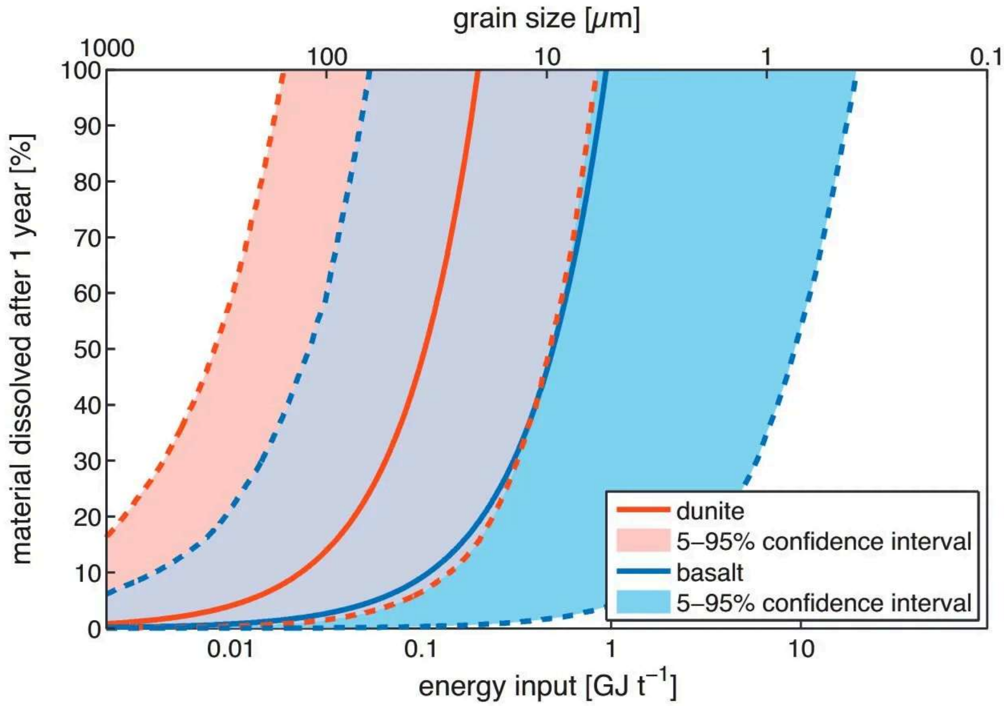


Fig. 2.2: Relationship between grain size, rate of dissolution and grinding energy (reproduced from *Strefler et al. 2018*).

- **Secondary precipitation -** During the initial stages of weathering the rate of dissolution is high. As the reactive phases are exhausted and the concentration of solutes in the solution increases, secondary amorphous phases, oxides and carbonates, among others, start to precipitate. While some studies reported no impact of secondary precipitation on ERW rates, others reported an increase. The effect of secondary precipitation on weathering rates is still disputed (Dupla et al 2025).
- **Soil pH -** The most prominent control on ERW rates is possibly pH. Most studies indicate that silicate weathering rates decreases with increasing pH or might follow a U-shaped curve, with neutral conditions showing the least amount of weathering. It is generally understood that acidic conditions (pH<6) favour mineral dissolution; although occasionally alkaline conditions (pH>9) can also increase mineral weathering (Fig. 2.3).

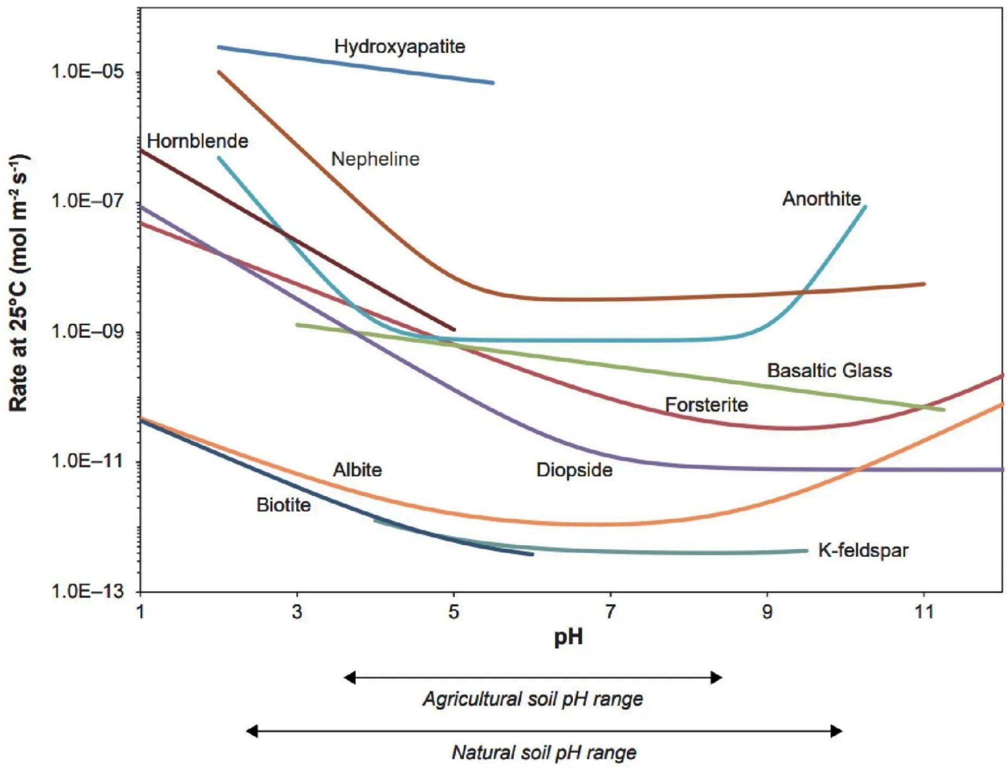


Fig. 2.3: Weathering rates of different minerals with respect to changing pH (reproduced from *Dupla et al. 2025*)

- **Plants -** Studies suggest that roots of plants can induce physicochemical conditions that favour silicate weathering (Vicca et al. 2022). Also, plants secrete organic compounds that help in chelating reaction products and dissolving silicate minerals even at near neutral pH.
- **Soil Enzyme -** Under conditions of nutritional deficiency and/or proximity to nutrient-rich minerals, plants release enzymes and proteins that may strongly influence silicate weathering processes in soil (Vicca et al. 2022). Carbonic anhydrases (CA), an enzyme vital to plant respiration, CO_2 transport and photosynthesis, is known to favour silicate weathering and precipitation of carbonates (Zaihua, 2001; Xiao et al. 2015).
- **Temperature -** Provided neither fresh supply of mineral nor water are a limiting criterion, weathering rates generally increases exponentially with temperature. However, the influence of temperature also depends on the field conditions (Fig. 2.4). For example, higher temperatures although favour faster weathering, can also cause faster evaporation affecting soil moisture (Dupla et al. 2025). Also, it is a known fact that increasing temperature reduces CO_2 solubility.

There are multiple factors in addition to the ones mentioned above like climate, saturation conditions, etc. that influence ERW.

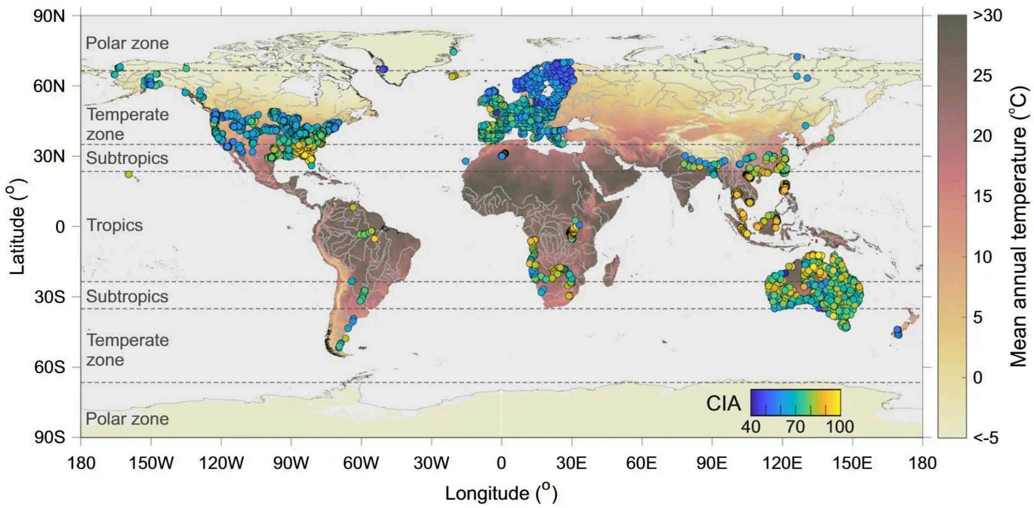
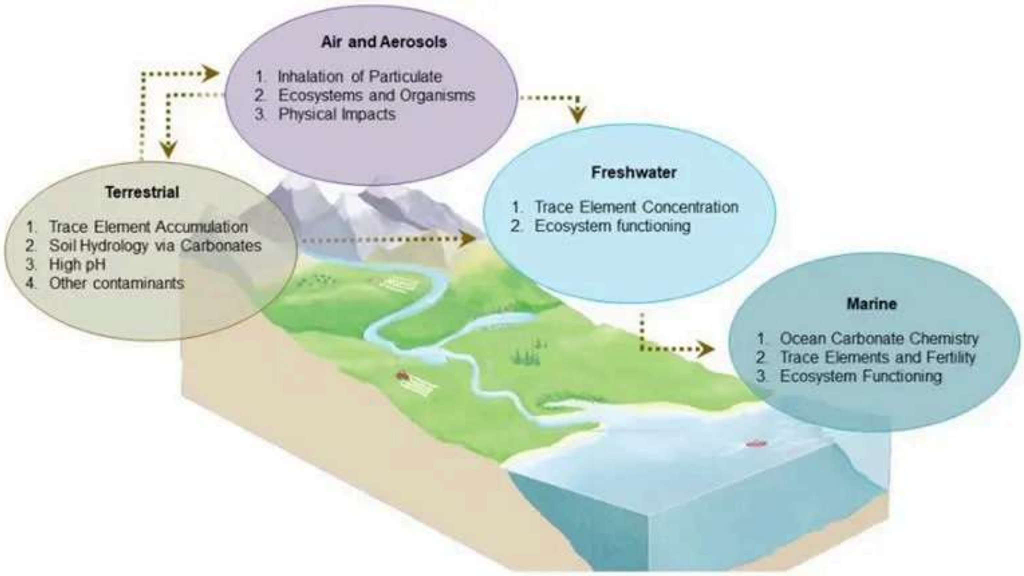


Fig. 2.4: Global map showing the chemical index of alteration across different climatic zones and temperatures (reproduced from *Deng et al. 2022*)

3. ENVIRONMENTAL AND SOCIAL IMPACTS



Fig, 3: Schematic diagram showing the different environmental effect of ERW (reproduced from *Levy et al. 2024*)

ENVIRONMENTAL EFFECTS

1. **IMPACT ON SOIL HEALTH -** The introduction of these minerals can alter soil porosity, moisture retention, and partial pressure of CO_2 within the soil profile. ERW can mitigate soil acidification common in intensively farmed areas and improve the availability of key nutrients such as calcium, potassium, and phosphorus for crops (Beerling et al. 2025). Continued research is needed into long-term effects on trace element accumulation in soil, organic matter changes, hydraulic conductivity, pH of freshwater bodies among others (Levy et al. 2024).
2. **IMPACT ON CROP HEALTH AND YIELD -** ERW has demonstrated a positive impact on crop health and yields by supplying essential micronutrients like zinc, copper, manganese, and iron; helping crops overcome common deficiencies and boosting their growth and productivity and improving plant resilience (Beerling et al. 2024). Results from field trials have shown both positive and neutral results with the application of basalt rock dust on crop yields.
3. **IMPACT ON WATERBODIES -** The impact of ERW is on both fresh and marine water bodies. ERW may mitigate freshwater acidification by increasing alkalinity and reducing proportion of dissolved organic carbon, but can mobilize trace elements.
4. **IMPACT ON AIR QUALITY -** The primary environmental concern on air quality due to ERW comes from rock dusts.
   Arnalds et al. (2016) studied the effect of basaltic dust in Iceland and concluded that they deteriorate air quality which leads to an increase in hospitalization. If coated by dust particles finer than 10µm, plants show a reduction in photosynthesis and may lead to die-back or death (Farmer, 1993; Kameswaran et al. 2019).
5. **IMPACT ON ECOSYSTEMS -** As the process of ERW raises soil pH, studies have documented a notable increase in bacterial and earthworm populations, which play critical roles in nutrient cycling and overall agricultural soil health. Previous studies (Thomson & Hoffman ,2007), illustrate how

ground covering techniques like straw and compost applications can affect belowground invertebrate populations. By analogy, and corroborated by more recent work, the addition of rock dust during ERW may similarly shape invertebrate communities in the soil (Levy et al. 2024).

SOCIAL IMPACTS

1. **IMPACT ON FARMERS AND MINERS -** The direct positive effects of ERW for farmers involve improvement in soil health and increase in crop yields (Beerling et al. 2018). Studies indicate that inhalation of silica-containing dust from farms may cause pneumoconiosis and lung inflammation in farmers in non-ERW settings itself. Any increase in rock extraction for ERW will aggravate the commonly associated risks with mining and affect mine workers too. Exposure to mine dust is a common health hazard faced by miners.
2. **IMPACT ON ECONOMY -** While existing research on its macro-economic effects remains limited (Oppon et al. 2023), the technology's integration into agricultural and industrial systems could stimulate new economic activities, particularly in sectors related to mining, logistics, and carbon credit markets. However, these economic benefits must be weighed against the costs associated with extraction, grinding, transportation, and field application of silicates, which could pose financial and environmental challenges if not managed efficiently (Lefebvre et al. 2019; Beerling et al. 2020; Smith et al. 2022).
3. **IMPACT ON GENDER -** Peer-reviewed literature that studies the awareness, views and impact of CDR technologies like ERW across demographic attributes like gender, age and socio-economic status although vital, remain low (Sovacool et al. 2024). Sovacool et al. (2024) in a recent survey across 30 countries worldwide (including India) found that support for ERW is higher in men compared to women, although the difference is less than 0.14 (on a scale of 1-5). Research related to climate science, policy and deployment in general suggests, that women are more vulnerable to the effects of extreme weather events in terms of monetary poverty, hunger, and exposure to violence among others (Patel et al. 2020; Caridade et al. 2022).

TRANSCRIPT

Hello everyone….

Today I am presenting a set of recommendations based on scientific literature and stakeholder engagement, meant as a policy framework related to enhanced rock weathering for India.

1. Introduction – Let us first understand the context of enhanced rock weathering. We all know, that the increase in human activities that emit greenhouse gases, especially CO2, has increased post industrialization era from around 1850. This has resulted in an increase in global average temperatures and it is increasing more and more with every passing day. In such a scenario, the use of carbon dioxide removal technologies becomes important along with reducing emissions. In this context, ERW is a novel CDR method that has the potential to not only sequester gigaton scale CO2 every year, but also improve soil health and help in increasing humanities food security.

So, what is enhanced rock weathering? It is the idea of enhancing or making faster the rock weathering process that occurs in nature and absorbs carbon dioxide from the atmosphere.

Natural rock weathering involves breaking of the rocks mechanically into smaller pieces. This is achieved in ERW by grinding rocks to micrometer sized particles using different equipment, or using existing rock dusts generated as a by-product of other processes. This grinding or mechanical breaking of the rock increases its reaction surface area, and as a result, the chemical weathering of this rocks happens much faster, compared to nature, where similar reactions may take thousands of years to complete. Water from rainwater or irrigation or in soil pores react with atmospheric CO2 to form carbonic acid. The proton from this carbonic acid helps in the dissolution of the silicate minerals, which are generally used for ERW. They do this by removing the cation from the lattice of this silicate minerals. The cation then either combine with the negatively charged carbonate anion and form some metal carbonates and precipitate. Or, they may remain in solution along with bicarbonates and migrate into rivers and streams, and eventually to oceans. The first pathway leads to a loss of 50% of the carbon dioxide originally removed from the atmosphere, which is returned back into the atmosphere.

2. Factors affecting ERW – A large number of factors can contribute to the rate of weathering of rock dusts. Mineralogy is one of the major factors in deciding successful weathering of ERW feedstocks within reasonable timescales. While some minerals like forsterite weather faster, others like k-feldspar weather much slower. Therefore, it is important to select a rock that weathers fast, for ERW. Weathering generally increases as the grain size of rock dusts decreases. If secondary minerals precipitates that can also have some impact on ERW rates. Soil pH is perhaps one of the most important factors, with acidic soils favouring ERW. But in case of some minerals alkaline conditions can also be beneficial. For example, if we have a rock rich in anorthite an alkaline soil can also be suitable. But, for most cases and most rocks, acidic conditions are preferable. Plants and other enzymes are also important in increasing the rate of chemical dissolution of silicate minerals in soils. Carbonic anhydrase is an important enzyme in this scenario, and have been highlighted often, in literature, as being suitable for use along with rock dust, to increase the rate of weathering. Temperature along with rainfall are also very important factors, as rock weathering is favoured in high temperatures and areas of high rainfall. That is why the chemical alteration of silicate minerals is generally highest in tropical climates.

3. Environmental and social impacts of ERW – Many of the negative and positive effects of enhanced rock weathering on the environment are well known, but lack of long-term research handicaps our understanding to a large degree. ERW can lead to positive effects such as reversing the effects of acidification, both in soil and water bodies. But it can also lead to leaching of potentially toxic elements such as nickel, chromium, etc., into soil and water bodies. Similarly, rock dusts can cause lung diseases in humans and damage plants. Results from field trials have shown both positive and neutral results with the application of basalt rock dust on crop yields. For example, studies by Oppong Danso et al. 2025, Skov et al. 2024 and Guo et al. 2023 showed an increase in crop yield which have reported yield increase in the range of ~7% - 77%, together with improved soil pH and nutrient uptake. On the contrary, some studies by Ramezanian et al. 2013 and Vienne et al. 2022 have reported no significant change in crop yield. Importantly, it should be noted, that the scarcity in the number of publications that report negative or neutral results may be a result of publication bias.

In terms of social impacts, ERW has the possibility to both positively affect farmers by improving soil health and crop yields, and also negatively impact farmer health due to dust inhalation. It also has the potential to positively improve job opportunities and at the same time lead to environmental degradation due to increased mining. Due to the long-term nature of ERW, there is not much literature studying their social impacts.

4. ERW potential for India – Multiple peer-reviewed publications have evaluated the potential of ERW in India, suggesting a high degree of suitability due to India's tropical climate and availability of the Deccan basalts as a major rock source. India has one of the largest CDR potentials in the world having extensive rock exposures and huge amount of farmland available for rock dust application. These factors are directly proportional to the feasibility and scalability of ERW. But there is a lack of field studies from India. Also, ERW is in its nascent stages in India, both across the public and private sectors.

5. Policy recommendations - The study takes a cradle to grave approach for policy recommendations. Due to the lack in scientific studies in local contexts we primarily suggest more pilot studies before large scale implementation. The safety and security of the farmers and miners involved should be the priority. We suggest the involvement of government agencies as that builds trust among the farmers, general public and to the carbon credit market. The study recommends testing all ERW feedstocks for potentially toxic elements using analytical instruments such as XRF, ICP-OES, ICP-MS, etc. The government should decide the limits for such elements based on local studies. Carbon accounting should be done for all the stages. Thorough quality checks and assurances are mandatory for each stage of the process.

TRANSCRIPT

ABSTRACT

Enhanced Rock Weathering (ERW) is a scientifically validated climate mitigation strategy that accelerates the natural geochemical breakdown of silicate rocks to capture atmospheric CO_2. When integrated into agricultural systems, ERW can also enhance soil fertility and crop yields. This study proposes a policy framework to facilitate ERW deployment in India, leveraging its tropical climate, high rainfall, abundant basaltic and ultramafic rock reserves and diverse agroecosystems. A preliminary literature review identified key technical and environmental variables (rock type, particle size, soil pH, temperature, potential trace element contamination etc.) that determine ERW's feasibility. Robust monitoring, reporting, and verification (MRV) systems are essential to assess carbon sequestration accurately. Despite growing scientific consensus, major gaps persist in field-scale weathering data, standardized MRV protocols, and long-term impact modelling. Stakeholder consultations revealed a lack of consensus regarding quantification of carbon dioxide removal (CDR), feedstock application frequency, regulatory ambiguity, and weak financial incentives as critical barriers. Our study identifies policy bottlenecks and maps institutional responsibilities essential for regulating ERW. For India to lead in scalable carbon dioxide removal, policy action must enable infrastructure development, inter-agency research collaboration, environmental safeguards, and carbon finance mechanisms. A dedicated, science-informed ERW policy could make CDR more efficient, equitable, and sustainable, while aligning with national climate and agricultural goals.

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RESIDUAL CONTENT

ACKNOWLEDGEMENT & REFERENCES (SELECTED)TE

EVALUATIONS

#	Average Score
There are currently no completed evaluations for this presentation	

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