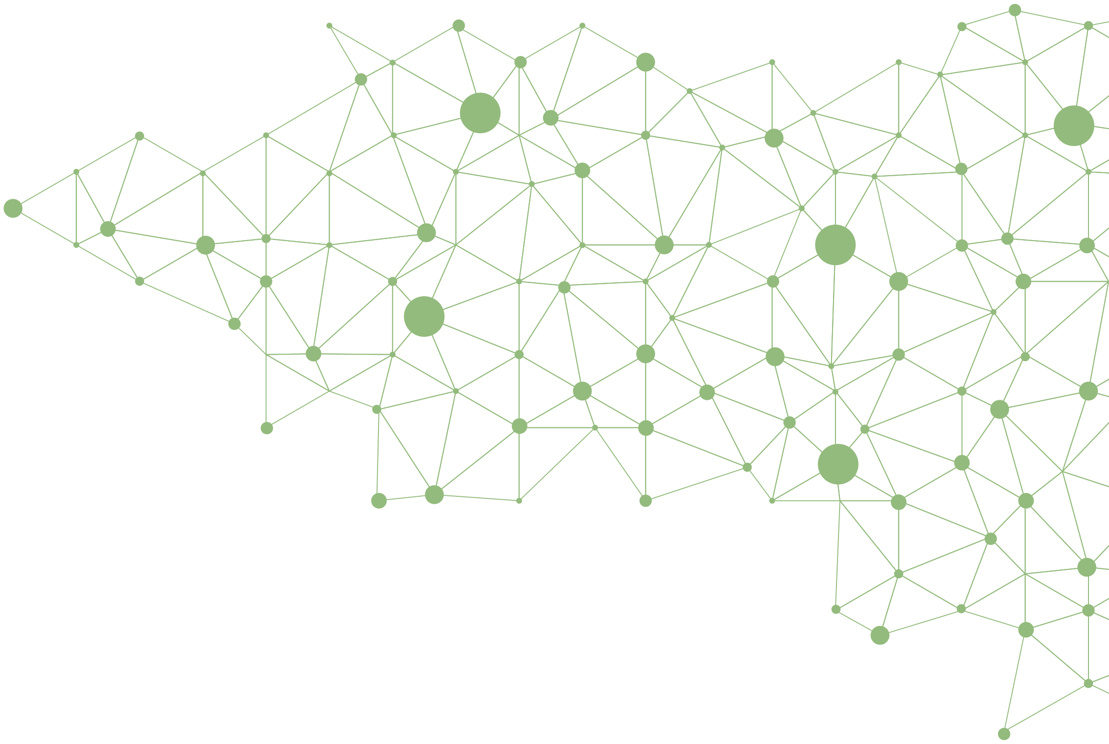
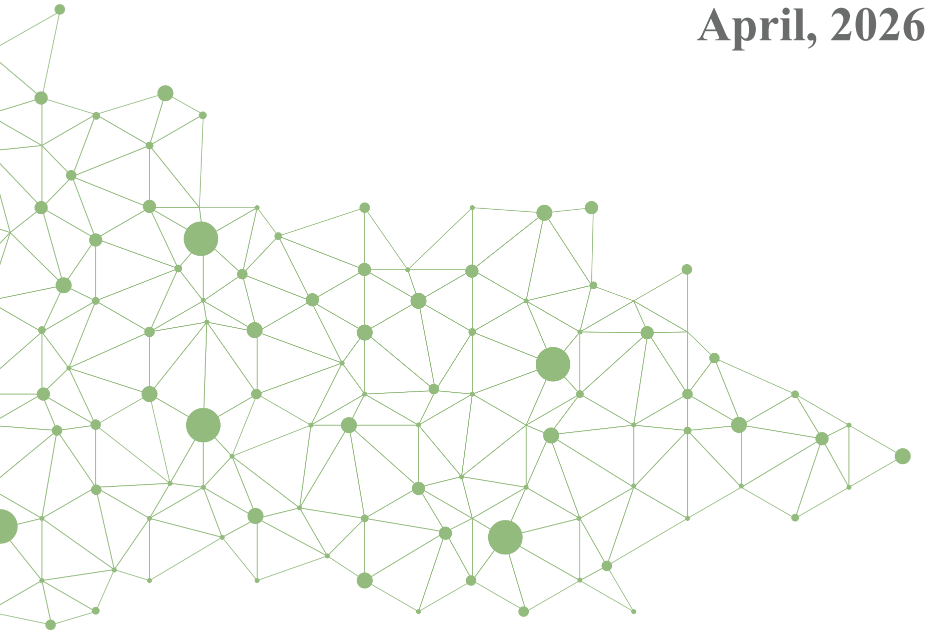


ASSESSMENT OF CURRENT PRACTICES IN ENHANCED ROCK WEATHERING AND DEVELOPING GOOD PRACTICES AND A POLICY FRAMEWORK FOR INDIA

Technical Report

April, 2026



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ASSESSMENT OF CURRENT PRACTICES IN ENHANCED ROCK WEATHERING AND DEVELOPING GOOD PRACTICES AND A POLICY FRAMEWORK FOR INDIA

TECHNICAL REPORT

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Disclaimer

While every effort has been made to ensure the accuracy and reliability of the information contained in this policy report on enhanced rock weathering, the authors and affiliated institutions do not accept any responsibility or liability for any errors of fact, omissions, interpretations, or opinions that may be expressed. This report draws on global best practices in science and policy to inform the development of a potential policy framework for India; however, it is intended for informational and advisory purposes only. The views and recommendations presented do not reflect the official position of the Government of India or any associated agency, or any stakeholder group. No responsibility is accepted for the consequences of any decisions or actions taken based on the use of this information.

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List of Abbreviations and Symbols

Ω	Saturation state
μm	Micrometre (micron)
AI	Artificial Intelligence
As	Arsenic
Ba	Barium
Be	Beryllium
BECCS	Bioenergy with Carbon Capture and Storage
BRSR	Business Responsibility & Sustainability Reporting
$°C$	degree Celsius
C	Carbon
Ca	Calcium
Ca^{2+}	Calcium cation
CA	Carbonic anhydrase
CCC	Carbon Credit Certificates
CCS	Carbon Capture Storage
CCTS	Carbon Credit Trading Scheme
CCUS	Carbon Capture Utilization Storage
Cd	Cadmium
CDM	Clean Development Mechanism
CDR	Carbon dioxide removal
CEC	Cation Exchange Capacity
CED	Cumulative Energy Demand
CGWB	Central Ground Water Board
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
Co	Cobalt
COP	Conference of Parties
Cr	Chromium
CRCF	Carbon Removal and Carbon Farming
CSR	Corporate Social Responsibility

CSIR	Council of Scientific & Industrial Research
Cu	Copper (*cuprum*)
DAC	Direct Air Capture
DACCS	Direct Air Capture and Carbon Storage
DIC	Dissolved Inorganic Carbon
DGMS	Directorate General of Mine Safety
DOCCS	Direct Ocean Carbon Capture And Storage
EC	Electrical Conductivity
EIA	Environmental Impact Assessment
EOR	Enhanced Oil Recovery
EPMA	Electron Probe Micro Analysis
ERW	Enhanced Rock Weathering
ESG	Environmental, Social and Governance
ETS	Emissions Trading System
EU	European Union
Fe	Iron (*ferrum*)
Fe^{2+}	Bivalent form of iron (ferrous)
FFZ	Far Field Zone
FPIC	Free, Prior, and Informed Consent
GCM	Global Carbon Market
GGR	Greenhouse Gas Removal
GHG	Greenhouse Gas
GPS	Global Positioning System
GSI	Geological Survey of India
Gt	Gigatonne
H^+	Positively charged hydrogen; due to the atomic structure of hydrogen this is often used to represent a proton. In this study this symbol is used to represent a proton
H_2CO_3	Carbonic Acid
H_2O	Water
ha	Hectare
HCO_3^-	Bicarbonate anion

Hg	Mercury (*hydrargyrum*)
IC	Integrated Circuit
ICAR	Indian Council of Agricultural Research
ICP-MS	Inductively Coupled Plasma - Mass Spectrometry
ICP-OES	Inductively Coupled Plasma - Optical Emission Spectroscopy
IIT	Indian Institutes of Technology
IPCC	Intergovernmental Panel on Climate Change
IUPAC	International Union of Pure and Applied Chemistry
JI	Joint Implementation
JTM	Just Transition Measures
kg	Kilogramme
km	Kilometre
K	Potassium
K^+	Potassium cation
KP	Kyoto Protocol
LCA	Life Cycle Assessment
Li	Lithium
LULU	Land Use, Land Use Change
LULUCF	Land Use, Land Use Change, Forestry
MAPA	Ministry of Agriculture, Livestock and Supply
Mg	Magnesium
Mg^{2+}	Magnesium cation
Mn	Manganese
Mo	Molybdenum
MoEFCC	Ministry of Environment, Forest and Climate Change
mol	Mole
MRV	Monitoring, Reporting, Verification
N	Nitrogen
NDC	Nationally Determined Contributions
NFZ	Near Field Zone
NITI Aayog	National Institution for Transforming India Aayog
Ni	Nickel

NMSA	National Mission for Sustainable Agriculture
NUE	Nitrogen Use Efficiency
OECD	Organisation for Economic Co-operation and Development
P	Phosphorus
PAT	Perform Achieve and Trade
Pb	Lead (*plumbum*)
PC	Pedogenic carbon
pH	activity of hydrogen ions in solution
PPE	Personal Protective Equipment
PSU	Public Sector Undertaking
PTE	Potentially Toxic Element
Q1	Quartile 1
Q2	Quartile 2
Q3	Quartile 3
RCP	Representative Concentration Pathway
R&D	Research and Development
Sb	Antimony (*stibium*)
Se	Selenium
Si	Silicon
SIC	Soil Inorganic Carbon
SiO_2	Silica
SOC	Soil Organic Carbon
SPCB	State Pollution Control Board
Sr	Strontium
t	tonne
TA	Total Alkalinity
Th	Thorium
Tl	Thallium
Ti	Titanium
TiCAT	Titanium-Cation
U	Uranium
USA	United States of America

V	Vanadium
VCM	Voluntary Carbon Market
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
yr	Year
Zn	Zinc

EXECUTIVE SUMMARY

1. Background and Rationale

Anthropogenic carbon dioxide (CO_2) emissions since the industrial era have driven unprecedented changes in the global climate system, placing the world on a trajectory that risks exceeding the critical threshold of 1.5°C above pre-industrial levels. Scientific assessments indicate that emission reductions alone will be insufficient to meet this target, necessitating the large-scale deployment of carbon dioxide removal (CDR) approaches. Among these, Enhanced Rock Weathering (ERW) has emerged as a promising, nature-based solution that accelerates the Earth's natural geochemical processes to remove atmospheric CO_2. In addition to its mitigation potential, ERW offers significant co-benefits for soil health and agricultural productivity. India is particularly well-positioned to leverage ERW due to its extensive agricultural base, favourable tropical and sub-tropical climatic conditions, and abundant availability of silicate rock resources, particularly basalt formations. Against this backdrop, the present report assesses current scientific understanding, global practices, and stakeholder perspectives to develop a comprehensive and precautionary policy framework for the safe and scalable deployment of ERW in India.

2. Study Objectives

This technical report was commissioned to assess global ERW practices, evaluate the scientific evidence base, engage stakeholders across the ERW value chain, and propose an evidence-informed policy framework tailored to India. The study pursued three primary objectives. First, it sought to draft policy guidelines that facilitate ERW adoption by mapping regulatory constraints, aligning with existing agricultural and environmental frameworks, and exploring targeted incentives. Second, it aimed to develop a practical implementation framework adaptable at local, district, state, and national levels across India's diverse agroecological contexts. Third, it establishes an analytical framework to evaluate environmental, economic, and social impacts, with particular attention to community livelihoods and equity considerations for marginalised populations.

3. Key Findings

3.1 Science and CDR Potential

ERW is based on the natural process of silicate weathering, through which atmospheric CO_2 is chemically transformed into other forms such as bicarbonates and carbonates. Under natural conditions, this process removes approximately 1.1 gigatonnes of CO_2 annually. ERW accelerates this process by mechanically reducing silicate rocks to fine particles increasing their reaction surface area, and applying them to soils - particularly agricultural lands. Atmospheric CO_2, along with CO_2 generated through root respiration and microbial activity in soils, dissolves in rainwater or soil porewater, to form carbonic acid. This weak acid subsequently reacts with silicate minerals, leading to the release of base cations (like potassium, calcium) and the formation of bicarbonate ions, thereby facilitating the long-term sequestration of carbon. These products may either precipitate as solid carbonates or remain dissolved and be transported to aquatic systems and eventually to the oceans, where carbon can be stored over long timescales. Although a portion of CO_2 is re-released during carbonate formation, the overall process remains net carbon negative. Current estimates suggest that ERW could remove between 300 and 5500 gigatonnes of CO_2 over the course of the 21st century, indicating its potential as a gigatonnes-scale climate mitigation pathway. Furthermore, the release of nutrients during mineral dissolution can enhance soil fertility, improve crop yields, and contribute to agricultural resilience, making croplands a particularly suitable setting for ERW deployment.

The effectiveness of ERW is governed by a range of interrelated geochemical, environmental, and biological factors. Among these, the type and composition of the feedstock material are of primary importance. Ultramafic rocks, such as peridotite and minerals like olivine, exhibit the highest weathering rates and carbon removal potential due to their base cation content and rate of weathering. Mafic rocks, particularly basalt, offer moderate weathering rates but are more widely available and generally present lower environmental risks, making them the preferred choice for large-scale application. In contrast, felsic rocks such as granite are significantly less reactive and therefore less suitable for ERW. Industrial by-products, including steel slag and construction waste, may serve as alternative feedstocks, although their lower carbon removal efficiency and potential contamination risks require careful consideration.

Particle size is another critical determinant of ERW performance. Finer particles provide a greater reactive surface area, thereby enhancing weathering rates and CO_2 uptake. However, the mechanical comminution required to achieve such particle sizes is energy-intensive and contributes to lifecycle emissions, creating a trade-off between increased reactivity and the overall CDR efficiency of the system. Soil properties also play a central role in governing reaction rates. Acidic soils with low soil pH generally facilitate faster weathering due to higher proton availability, while neutral or alkaline conditions tend to slow the process. Soil moisture is equally important by promoting the acid hydrolysis process that is ERW. Soil saturation conditions are also important as the ERW process is primarily driven by chemical disequilibrium between the minerals and soil porewater. Additional soil characteristics, including cation exchange capacity, porosity, and mineral composition, further influence the extent and rate of carbon sequestration. At the same time, the formation of secondary minerals on particle surfaces may inhibit further reactions over time, highlighting the importance of long-term system dynamics.

Climatic conditions exert a strong influence on ERW processes. Higher temperatures accelerate mineral dissolution rates, while increased precipitation enhances chemical reactions and the transport of dissolved carbon species. As a result, tropical and sub-tropical regions, such as much of India, are particularly well-suited for ERW deployment. Seasonal variability and extreme weather events, including droughts and floods, can further affect weathering dynamics, either enhancing or constraining the process. Biological factors also contribute significantly to ERW effectiveness. Plants, microbes, and soil fauna facilitate mineral breakdown through root exudates, enzymatic activity, and physical soil disturbance, thereby accelerating weathering rates.

Despite its strong theoretical foundation, ERW remains an emerging technology with several critical uncertainties. A central challenge lies in the measurement, reporting, and verification (MRV) of carbon removal. Given the open and complex nature of soil systems, direct quantification of CO_2 sequestration is difficult, and current methodologies rely heavily on indirect indicators such as changes in soil chemistry, alkalinity, and dissolved inorganic carbon. This introduces significant uncertainty into carbon accounting. Furthermore, a notable discrepancy exists between laboratory and field studies, with controlled experiments and models often overestimating weathering rates compared to real-world conditions. The lack of long-term field data, particularly in the Indian context, further limits confidence in projections of carbon removal potential and environmental impacts. These uncertainties also raise concerns regarding the potential over-crediting of carbon removal, which could undermine the credibility of carbon markets and associated climate mitigation efforts.

3.2 Agricultural and Environmental Co-benefits

The application of silicate rock dust can improve soil fertility by supplying essential nutrients, stabilizing soil pH, and enhancing microbial activity, thereby supporting increased agricultural productivity. Field trials from various countries report crop yield increases ranging from around 7% to 77%, depending on crop type, rock amendment, and soil conditions. ERW supplies essential macro- and micronutrients (calcium, magnesium, potassium, silicon, iron) and acts similar to a liming agent that counteracts soil acidification, a widespread problem in tropical farmlands. Silicon uptake from weathering products can strengthen plant tissue and improve resilience to abiotic stresses such as drought, heat, and salinity, while also limiting uptake of toxic heavy metals. These co-benefits position ERW not merely as a carbon removal tool but as a soil health intervention with the potential to reduce dependence on synthetic fertilisers. Changes in water chemistry resulting from runoff and leaching may affect freshwater and marine ecosystems, with both beneficial and potentially adverse outcomes depending on context. At the ecosystem level, increased biological activity may enhance soil biodiversity, although cascading ecological effects remain insufficiently understood.

3.3 Environmental and Health Risks

ERW deployment carries environmental risks that demand careful management. Dust generated during grinding, transport, and field application poses inhalation hazards, particularly from respirable crystalline silica and trace potentially toxic elements. Potentially toxic elements such as nickel, chromium, lead, cadmium, and arsenic present in certain rock feedstocks can contaminate soils and leach into groundwater and surface water bodies. Over-application of fine rock powder may alter soil porosity and hydraulic conductivity, affecting water infiltration and potentially increasing surface runoff. Downstream effects on freshwater alkalinity, aquatic ecosystems, and marine chemistry require monitoring, particularly at scale. A sustainability assessment indicates that India faces the highest vulnerability among countries studied in terms of human health impacts from large-scale ERW deployment, underscoring the need for robust safety protocols.

3.4 Social and Economic Impacts

Social and economic considerations are equally significant. ERW has the potential to increase farm productivity and generate new economic opportunities in sectors such as mining, logistics, and carbon markets. However, benefits may not be equitably distributed, particularly in contexts characterized by insecure land tenure or limited institutional capacity. Workers involved in mining and application processes may face occupational health risks, particularly from dust exposure. Additionally, there is a notable lack of gender-disaggregated research on ERW, although broader evidence suggests that women in the Global South may face greater barriers to participation and may perceive higher environmental risks. These considerations underscore the need for inclusive and socially responsive policy frameworks.

3.5 Global Policy Landscape

The policy landscape for ERW remains underdeveloped both globally and in India. A review of ERW-related policy across Brazil, China, the USA, the UK, Canada, and the EU reveals a common pattern: no country has enacted dedicated ERW legislation. ERW governance currently rests almost entirely on voluntary carbon markets and private sector initiatives. Registries such as Puro.Earth and Isometric have developed ERW-specific protocols, and large corporate buyers, notably Microsoft, account for a significant share of ERW credit purchases. The voluntary carbon market has grown from 5 million credits in 2007 to over 286 million in 2023, with a market value exceeding USD 4 billion. However, this private-sector-driven model is fragile, dependent on a small number of buyers, and lacks the regulatory certainty needed for sustained, large-scale deployment.

Countries from the global north are in a better position in this regard supporting, research and development and policy frameworks related to ERW. In India, policy efforts have focused primarily on land-use and carbon capture technologies, with no integration of ERW into national strategies. This creates a significant gap in terms of regulatory clarity, standard-setting, and institutional coordination. The absence of standardized MRV frameworks and domestic carbon credit mechanisms further constrains the development of a credible and scalable ERW ecosystem. Brazil offers a partial precedent through its classification of silicate rock powders as 'remineralizers' under agricultural law, with mandated geochemical and safety testing. The EU is developing a Carbon Removal and Carbon Farming regulation that may incorporate ERW. India's Carbon Credit Trading Scheme, adopted in July 2024, does not yet recognise ERW as an eligible methodology.

3.6 Prevalent Global Good Practices

Current practices are best understood through a lifecycle perspective, encompassing feedstock sourcing, processing, transportation, application, and monitoring. Energy use in grinding operations can account for a significant share of lifecycle emissions, while transportation—particularly over long distances—often represents a large contributor to the overall carbon footprint. Consequently, local sourcing of materials is critical to ensuring net carbon removal. Field application typically relies on existing agricultural machinery, although operational efficiency and fuel use influence emissions. Robust MRV systems are widely recognized as essential for ensuring credibility, yet current approaches rely heavily on modelling and indirect measurements, reflecting ongoing scientific uncertainty. Policy support for ERW is uneven, with greater activity observed in developed economies, where public funding, research initiatives, and pilot projects are more advanced. In contrast, developing countries, including India, have significant potential but lack dedicated policy frameworks and institutional support.

Drawing from both global experience and existing literature, a set of integrated best practices can be identified for ERW deployment. These include careful selection of feedstock materials based on mineral composition, reactivity, cost, and environmental safety, with particular emphasis on avoiding materials containing toxic elements, asbestos, sulphides, or radioactive components. The use of existing quarry waste and mine tailings is recommended to minimize environmental impacts associated with new mining. Processing should prioritize energy efficiency and, where feasible, the use of renewable energy sources. Transportation distances should be minimized to reduce emissions, and low-carbon logistics should be encouraged. Application rates should be tailored to site-specific conditions, as excessive application may not yield proportional benefits and could lead to nutrient imbalances. Environmental and occupational safeguards, including dust suppression and worker protection measures, are essential. Finally, MRV systems should incorporate baseline assessments, continuous monitoring, standardized reporting, and independent verification to ensure transparency and credibility.

3.7 Stakeholder Perspectives

Structured engagement with researchers, project developers, carbon market actors, and practitioners yielded broad consensus on several points including, the scientific validity and potential benefits of ERW, as well as on the importance of agricultural deployment and co-benefits for soil health. Basalt is the preferred feedstock owing to its global availability, nutrient profile, and relatively lower risk of toxic element contamination. Agricultural croplands, particularly rice paddies, are the most promising deployment ecosystems in India. Rock sourcing should remain within approximately 100 km of application sites to maintain a favourable life cycle assessment. Waste rock and crusher by-products should be prioritised over freshly mined material. Monitoring, Reporting, and Verification (MRV) was identified as the single largest cost driver in ERW projects, often consuming 70–80% of total expenditure in small-scale initiatives. There is also consensus on the central role of MRV in ensuring credibility, although views differ regarding the appropriate balance between precision and cost-effectiveness. Stakeholders strongly emphasize the need for a clear and dedicated policy framework in India, along with robust regulatory oversight, institutional coordination, and the development of a domestic carbon market. At the same time, divergent perspectives exist regarding the degree of centralization, with some advocating for comprehensive national regulation and others favouring more flexible, decentralized, or phased approaches.

Stakeholders also flagged critical barriers: unreliable farmer participation, high upfront capital requirements, limited buyer demand for high-cost durable carbon credits, inadequate infrastructure and logistics, and the absence of a supportive policy ecosystem. Several practitioners emphasised that communicating agronomic co-benefits to farmers is more effective for securing participation than framing ERW purely as a carbon market intervention.

3.8 ERW in India: Current Status

Enhanced Rock Weathering (ERW) in India remains at an early stage in both public and private sectors. To date, there are no peer-reviewed studies evaluating ERW in agricultural settings, though some feasibility assessments for the Indian context have been conducted. Research on the general chemical weathering of silicate rocks, its impact on river and groundwater chemistry, and related CO_2 sequestration exists. Currently, only a limited number of research groups, notably at the National Centre for Earth Science Studies in Trivandrum, are actively exploring ERW applications in agriculture. Four private companies, Alt Carbon (Darjeeling, West Bengal), Mati Carbon (Chhattisgarh, Madhya Pradesh, Jharkhand), Varaha (Madhya Pradesh), and Everest Carbon, have initiated pilot and early-commercial projects.

4. Summary of Key Findings

Theme	Key Finding
CDR Potential	Global estimates range from >300 Gt CO_2 to 5500 Gt CO_2 during the 21st century. Basalt alone can sequester 230–250 kg

Theme	Key Finding
	CO_2 per tonne of rock. India ranks among the top three nations for ERW potential alongside China and the USA.
Agricultural Co-benefits	Field trials report crop yield increases of approximately 7–77% depending on rock type, soil, and crop. ERW improves soil pH, nutrient availability (Ca, Mg, K, Si, Fe), and reduces dependence on synthetic fertilisers.
India's Advantages	Extensive Deccan and Rajmahal basalt deposits, large cropland area, tropical climate with high rainfall and temperature, and low operational costs make India highly suited for ERW deployment.
Current Gaps	No peer-reviewed field study from India on ERW in agriculture. Universally accepted methods for measuring CDR from ERW are absent. Long-term field data remain scarce globally. Like most countries, India lacks regulations laying out the maximum concentration of potentially toxic elements permissible in soil
Policy Vacuum	India lacks a dedicated ERW policy, ERW-specific MRV standards, and a domestic carbon credit registry. ERW is not recognised under the Carbon Credit Trading Scheme (2024). Additionally, India, similar to many other countries, does not have regulatory guidelines specifying the maximum allowable concentrations of potentially toxic elements in soil.
Environmental Risks	Dust generation, potentially toxic element contamination (Ni, Cr, Pb, Cd, As), soil structure alteration, and potential leaching into water bodies require rigorous monitoring and feedstock screening.

5. Recommendations to Advance Policy that Supports ERW Adoption in India

The report proposes a comprehensive, life-cycle-based policy framework for ERW in India, with recommendations organised across five stages of the ERW value chain: mining and extraction, feedstock preparation, transport, field application, and long-term monitoring.

Institutional Architecture: India's ERW landscape currently has no coordinating body, no agreed standards, and no single ministry with a clear mandate. That needs to change before projects scale beyond the pilot stage.

To enable large-scale deployment, the report recommends a range of financial and institutional measures, including the integration of ERW into national climate and agricultural policies, the provision of incentives for farmers, and the facilitation of access to finance through public and private institutions. The report recommends establishing a Nodal ERW Committee under the NITI Aayog or Ministry of Environment, Forest and Climate Change or Bureau of Energy Efficiency to coordinate across the Geological Survey of India (GSI), Directorate General of Mines Safety (DGMS), State Pollution Control Boards, Departments of Agriculture, Transport, and Water Resources, and local governance bodies The GSI already holds lithological and geochemical maps that are directly relevant to feedstock assessment. Formalising its advisory role in certifying ERW feedstocks is a practical use of existing capacity and avoids creating new bureaucratic layers from scratch.

Feedstock Sourcing: Prioritise Waste Materials: Opening new mines purely to supply ERW feedstock is difficult to justify at this stage. The lifecycle emissions from fresh extraction and the ecological disruption involved often undermine the very rationale for ERW. India produces large volumes of quarry waste, mine overburden, and crusher by-products that currently sit unused. These materials should be the first source for any ERW project.

The DGMS, working with the GSI, should identify and reclassify suitable mine overburden and tailings as ERW feedstocks, subject to proper geochemical screening. Steel slag from India's iron and steel industry, warrants particular attention, but must be assessed batch by batch before any agricultural application.

Feedstock Quality Control: Mandatory pre-deployment testing of every batch of ERW feedstock using XRF or ICP-MS or ICP-OES for oxide composition, ICP-MS for toxic elements, and XRD or EPMA for mineralogical characterisation. It is recommended that analyses should be conducted through accredited laboratories at IITs, CSIR institutions, or State Agricultural Universities and the data should be made publicly available. Batches exceeding safe thresholds for potentially toxic elements must be rejected. Similarly, feedstocks with potentially harmful concentrations of asbestos minerals, sulphide minerals and radioactive elements must be avoided.

Transport and Logistics: There are no ERW-specific transport rules in India. In the interim, aligning with the Fly Ash Notification of 1999 and its amendments provides a reasonable starting point for managing fine particulate materials during transport. However, this should be understood as a temporary measure. India should develop ERW-specific transport guidelines within a defined timeframe, given that rock dust characteristics differ from fly ash in important ways.

Rock powder should be moved in sealed bulkers or covered vehicles. Dust suppression systems should be mandatory at loading and unloading points. Transport distances should ideally stay around 100 kilometres of the application site; beyond this, the lifecycle carbon benefit can erode considerably depending on the fuel and vehicle type. Although this distance can vary widely depending on a large number of factors ranging from carbon sequestration goal of the project to carbon sequestration potential of the material used to nature of transport used. Digital chain-of-custody records should track material from quarry or processing unit to farm, and this data should feed into MRV records.

Field Application Standards: Application rates should be determined through baseline soil testing and carbon uptake modelling, with reference and trial plots maintained for ongoing comparison. It should depend on local soil chemistry and other local factors. Written farmer contracts should specify consent, benefit-sharing terms, data-sharing obligations, project duration, and dispute resolution mechanisms. These contracts need to be translated into local languages and should not rely on literacy for comprehension; audio or video explanations in regional languages should accompany written forms where literacy levels are low. Coordination with Panchayats, District Administrations, and Departments of Agriculture is essential.

National MRV Protocol: MRV is, in the words of most practitioners, the single biggest cost in any ERW project. The report recommends that India should develop and publish an ERW-specific MRV methodology aligned with international best practices. A nationally standardised protocol would help reduce this burden, but it needs to be calibrated to project size. The protocol should specify carbon accounting boundaries, sampling methods and depths, verification intervals, laboratory standards, uncertainty handling, permanence criteria, additionality tests, and leakage assessment. Data from MRV processes should be published in peer-reviewed international journals for the first few years of any ERW project. Third-party verification should be mandatory. The framework emphasizes the importance of adaptive governance, with mechanisms for periodic review and revision to incorporate new scientific evidence and respond to emerging risks into national MRV protocols. The protocol should be housed with a technical body, ideally the GSI in collaboration with ICAR, rather than left to voluntary carbon registries to define.

Domestic Carbon Credit Framework: India's Carbon Credit Trading Scheme (CCTS), does not yet include ERW as an eligible methodology. This should change. Including ERW under the CCTS linked to the nationally determined contributions under the Paris Agreement, with a methodology aligned to national MRV standards, would unlock domestic demand for removal credits and provide the market signal that project developers currently lack. Steps must be taken to prevent double counting of CDR credits. A strong domestic carbon market is necessary to scale ERW in India. Incorporating ERW into Corporate Social Responsibility regulations and existing ESG reporting frameworks for eligible Indian companies would create a domestic demand base that is currently missing. High credit prices and low awareness among Indian corporates are the two main barriers to ERW credit uptake. Awareness programmes targeting compliance teams in large emitting industries could address both barriers simultaneously.

Environmental Safeguards: Strong environmental safeguards are recommended across all stages, including dust control, worker safety protocols, land rehabilitation, and the protection of soil and water resources. India also urgently needs to establish maximum permissible limits for potentially toxic elements in agricultural soils. Formulating these limits should be treated as a priority task taking into account India’s diverse agro-climatic conditions and variety of ecosystems. Regular monitoring of soil and water quality is also strongly recommended for all ERW projects. Both baseline and regular monitoring of water bodies and soil is recommended throughout the project lifetime.

Dust is the most immediate occupational hazard in ERW operations. Workers involved in grinding, loading, transporting, and field spreading are at risk of inhaling respirable crystalline silica. Personal protective equipment alone is insufficient at the scale envisaged; engineering controls, including enclosed grinding facilities, wet suppression during application, and mandatory health monitoring for workers in high-exposure roles, should be required for all projects.

Community Safeguards and Equity: One of the most consistent findings from stakeholder consultations is that farmer participation in ERW is unreliable, partly because farmers are sceptical about new soil interventions and partly because they have no financial safety net if something goes wrong. Linking ERW adoption to India's existing crop insurance infrastructure offers a practical solution. Farmers who enrol in certified ERW programmes should be incentivised under the Pradhan Mantri Fasal Bima Yojana. This creates a risk-sharing mechanism without requiring entirely new institutional machinery. It also reframes ERW in terms that farmers understand, namely protection against loss rather than abstract carbon markets.

The report recommends that policy must ensure that smallholder farmers, particularly those in tribal and marginalised communities, receive equitable benefits. Land ownership documentation issues, which frequently exclude smallholders from fair compensation, require targeted attention. Valid land ownership should be mandatory for application of ERW in the specific land. Free, Prior, and Informed Consent and transparent benefit-sharing mechanisms must be embedded in all project designs. Local institutions, including Panchayats, are identified as critical actors in monitoring, community engagement, and grievance redressal.

Research Priorities: India urgently needs primary field trials across its different agro-climatic zones to generate locally relevant evidence on crop yields, soil chemistry, environmental and socio-economic impacts. Studies addressing long-term effects on trace element accumulation, soil organic matter, freshwater alkalinity, soil parameters and gender-differentiated impacts should be pursued. Research on the potential and risks of different rock types and industrial by-products as ERW feedstocks should be encouraged. Explore the use of organic compounds alongside silicate rock powders.

6. Conclusion

Enhanced Rock Weathering holds considerable promise as a scalable, nature-based carbon removal strategy with meaningful co-benefits for soil health and agricultural productivity. India’s geological resources, tropical climate, extensive cropland, and low operational costs place it among the most favourably positioned countries for ERW deployment. However, the transition from pilot projects to responsible, large-scale implementation demands a coordinated policy response. The scientific evidence base, while encouraging, remains insufficient to support deployment without rigorous, locally generated field data and robust MRV systems.

This report provides a foundation for informed policy action. It recommends a phased approach: invest in multi-site field research, establish feedstock quality and safety standards, build institutional capacity for monitoring and regulation, develop a national MRV protocol, create a domestic carbon credit framework, and embed equity and community participation at every stage. If these steps are taken with scientific rigour and political commitment, ERW can become a meaningful component of India’s climate strategy, contributing to carbon removal, food security, and rural livelihoods simultaneously.

A well-designed and adaptive policy framework will be essential to ensure that ERW is deployed responsibly, effectively, and at scale, positioning India as a leader in the development of sustainable and innovative climate solutions.

CHAPTER 1 – INTRODUCTION

1.1. Overview

The continued emission of carbon dioxide and other greenhouse gases into the atmosphere by humans over the last 150 years have raised global average temperatures to approximately 1.2°C compared to preindustrial era (WMO, 2021). The rate at which our planet is heating up has only accelerated with time (National Oceanic and Atmospheric Administration, 2021). Global warming affects humanity both directly and indirectly. It leads to more frequent and extreme weather events, environmental degradation (which includes soil; vegetation; forests; water resource) and rise in sea level due to thermal expansion of seawater and addition of water melted from glaciers. The latest report from the Intergovernmental Panel on Climate Change (IPCC) warns that to keep the global temperature rise to 1.5°C above pre-industrial levels, we must urgently control carbon dioxide (CO_2) emissions (Fig. 1.1). Current global plans to reduce greenhouse gases are not enough; if no stronger actions are taken soon, we will likely exceed this critical temperature threshold during this century (Intergovernmental Panel On Climate Change (IPCC), 2023). Exceeding 1.5°C will greatly increase the risks of severe and irreversible climate impacts, threatening communities, ecosystems, and economies worldwide. Immediate and deep cuts in emissions, combined with measures to remove CO_2 from the atmosphere, are essential to avoid catastrophic consequences and meet international climate goals (Cox et al., 2022).

Evaluation of various climatic scenarios by IPCC show that, just reduction in carbon dioxide emissions alone will not be able to achieve this. Carbon dioxide removal (CDR) technologies which removes existing CO_2 from the atmosphere, are an integral part of achieving this target. In the Fifth Assessment Report of the IPCC, 104 pathways out of 116 depend on CO_2 removal technologies to achieve the aforementioned target (Fuss et al., 2016). Currently, CDR projects are considered controversial due to well-founded concerns regarding use of under-developed technologies along with other social, environmental, ethical and political concerns (Cox et al., 2018; Honegger et al., 2021).

In recent times, Enhanced Rock Weathering (ERW) has been recognised as a new and novel approach for CDR (Manning, 2025). The ERW approach is based on the simple idea of accelerating or enhancing the natural rock weathering process. In nature, rocks weather through a combination of both mechanical and chemical processes (Tarbuck and Lutgens, 2012). Mechanical weathering involves the breaking up of rocks into smaller fragments without any change in their chemistry. Chemical weathering on the other hand, leads to the transformation of the rock in terms of chemical composition, and results in the formation of one or more new compounds. This natural weathering process removes atmospheric CO_2 via dissolution of silicate or carbonate minerals. The natural weathering process will eventually capture all CO_2 released due to human activity, but it is a slow process and this carbon capture will occur over geological timescales (Archer et al., 1997).

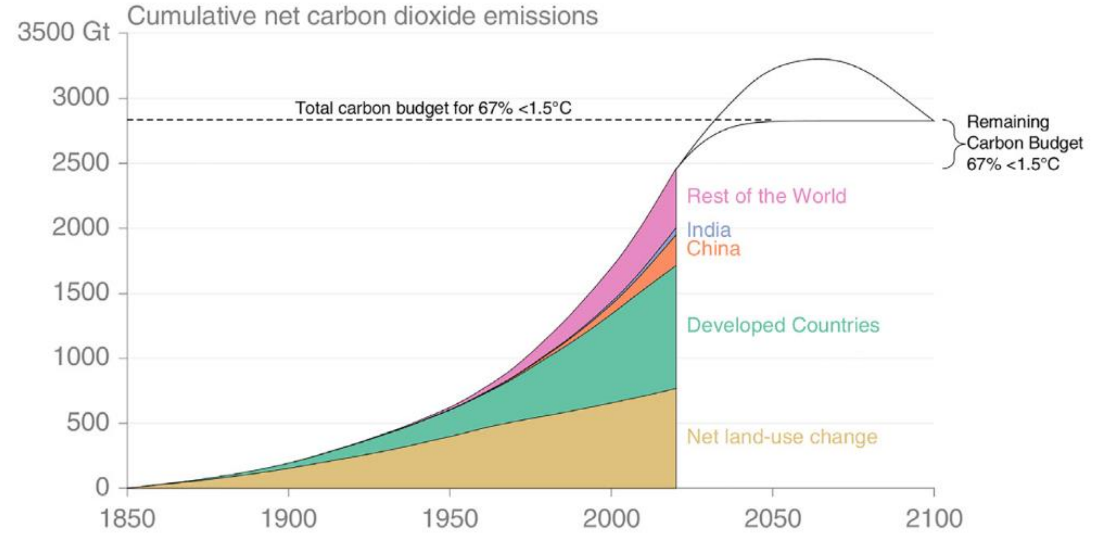


Fig. 1.1: Cumulative CO_2 emission from 1850 and possible future paths to prevent temperature rise within 1.5°C. Cumulative CO_2 emissions are calculated from the Global Carbon Project, the remaining carbon budget for 1.5°C (with a 67% chance – IPCC AR6 WG1) is also shown. Emissions from non-CO_2 sources is also added in the temperature limit (reproduced from Mohan et al., 2021).

ERW generally involves mixing crushed/powdered calcium- and/or magnesium-rich silicate rocks with soil to fasten the process of carbon capture (Fig. 1.2). Land based application of ERW in croplands have the added advantage of increasing agricultural yield and reducing CO_2 emissions related to agriculture (Baek et al. 2017; Skov et al. 2024; Beerling et al. 2025). The fact that annual exchange of CO_2 between the soil-plant system and the atmosphere accounts for around a sixth of total atmospheric CO_2, makes ERW a very promising CDR strategy (Manning, 2025). Currently, the idea of enhanced rock weathering is actively researched across three environments viz, ocean, coastal and terrestrial (Dupla et al., 2025). The term 'enhanced rock weathering' (ERW) is used interchangeably with the term 'terrestrial enhanced rock weathering' in the literature. The 'terrestrial' term is used to differentiate it with ocean alkalinity enhancement, another CDR approach that involves using rock powder in the ocean or along coasts. In this study, the term 'Enhanced Rock Weathering' is used and refers to the land-based application of ERW and not across oceans and coasts.

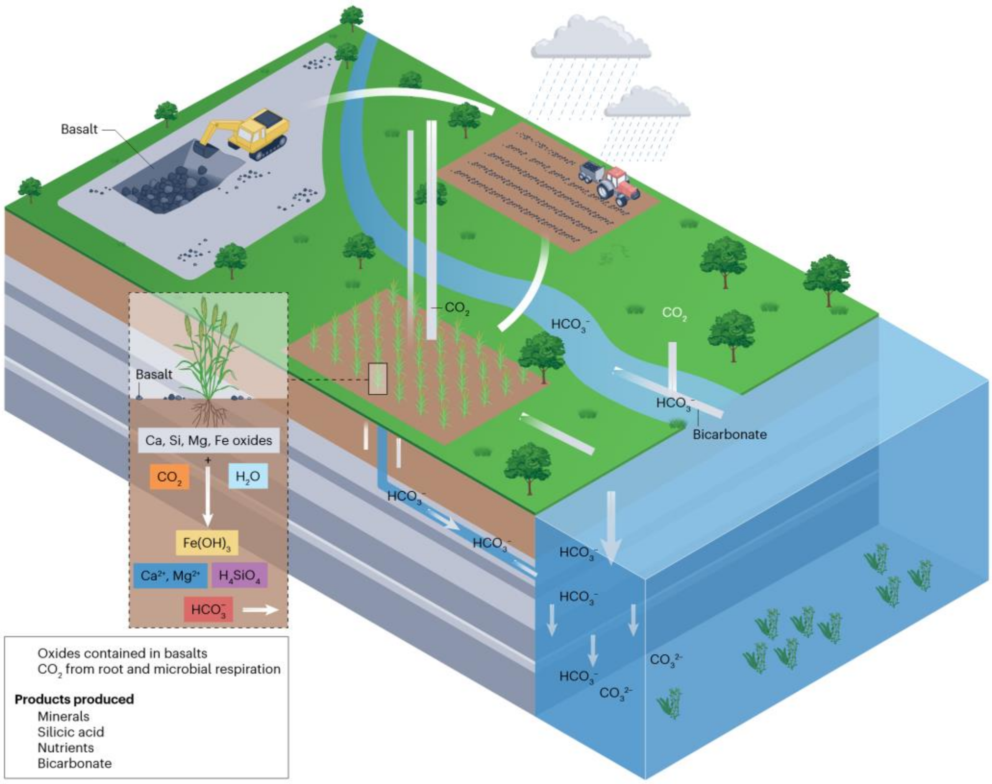


Fig. 1.2: Overview of the process of enhanced rock weathering (shown in this case for basalt). Also shown are the basic chemical reactions that lead to the weathering process (reproduced from Beerling et al. 2025).

1.2. Objectives

Despite the growing recognition of Enhanced Rock Weathering (ERW) as a promising carbon dioxide removal strategy, several critical gaps remain in current understanding, policy, and implementation practices. Current understanding of the effectiveness of ERW is still insufficient to formulate dependable predictive capabilities (Dupla et al. 2025). While India is well-positioned to lead in ERW deployment, existing practices must be assessed to uncover key insights that can shape scalable and context-specific solutions. A lack of comprehensive research into ERW's full life cycle—including rock sourcing, application methods, and local adaptation—highlights the necessity of a coordinated national policy which supports research, development and application programmes. Moreover, identifying logistical barriers, policy voids, and factors influencing success is essential to support widespread ERW adoption. Therefore, there is an urgent need to develop an informed, evidence-based policy framework that addresses environmental and socio-economic implications specific to India's diverse agricultural and geological contexts. Addressing these challenges will lay the foundation for effective, scalable interventions that align with India's climate strategy to build resilience and sustainable agriculture goals, and meeting CDR goals.

In this context, the project focuses on three primary objectives:

- Policy Guidance: Draft policy guidelines to facilitate ERW adoption and expansion, including mapping constraints and solutions, integrating regulatory frameworks, aligning with agricultural and environmental policies, and exploring targeted incentives or subsidies.
- Implementation Framework: Develop a practical framework for ERW deployment adaptable at local, district, state, and national levels, ensuring effectiveness across diverse agroecological contexts.
- Impact Analysis: Establish an analytical framework to evaluate environmental, economic, and social impacts of ERW practices, prioritizing community livelihoods and aligning interventions with India’s unique landscapes and farming systems.

To assess ERW’s suitability as a long-term, nature-based climate solution centred on people, the following guiding questions are critical (Henfrey et al., 2023; Seddon et al., 2021; Dutta, S.- LinkedIn post):

- Community Engagement: Is the initiative community-led or merely community-involved? Are local voices genuinely included in decision-making?
- Ownership and Benefit Sharing: Who controls resources and benefits? Are rights clear and equitable, particularly for women and marginalized groups?
- Consent: Was Free, Prior, and Informed Consent (FPIC) obtained? Are risks and trade-offs communicated in local languages with ongoing feedback mechanisms?
- Stewardship: Does traditional knowledge guide ERW practices? Are local stewards leading implementation and decisions?

- Systemic Impact: Does the approach build enduring systems, address root causes, and strengthen networks, skills, and institutional capacity, rather than functioning as a one-off project?

  Addressing these questions will ensure that ERW interventions are not only technically effective but socially inclusive, environmentally responsible, and scalable, providing a robust pathway for India to meet climate, agricultural, and community resilience objectives.

CHAPTER 2 - LITERATURE AND POLICY REVIEW

The current policy study deals with assessing enhanced rock weathering practices and policies worldwide to propose a policy framework for India. ERW is a CDR technique that mixes pulverised typically calcium- and magnesium-rich silicate rocks with soil to speed up CO_2 sequestration (carbon capture and storage), with the added benefit of increase in crop production and improvement in soil health (Beerling et al., 2020). In the present study, we focus on ERW in open systems. Study of weathering processes in closed systems is also currently being done (e.g., (Pogge Von Strandmann et al., 2025), but is out of the scope of the current study.

2.1. Literature Review

2.1.1. The Basics

The weathering process in general maybe understood as a process in which cations are released from silicate minerals (Fig. 2.1; Table 1). These cations which were previously held within the silicate structure cannot exist alone and needs an anion to balance their positive charges. In natural weathering processes, mostly bicarbonate (formed from atmospheric CO_2 and rainwater or aerobic respiration of plants and microbes in soil solution) acts as this counter-balancing negative charge. The silicate component on the

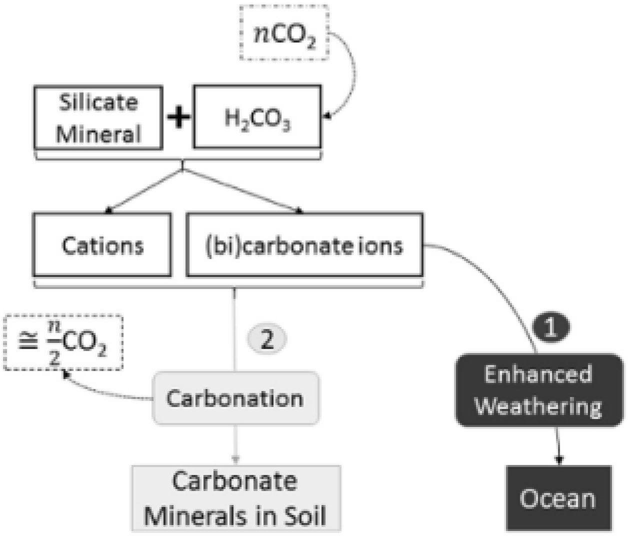


Fig. 2.1: Flowchart showing the typical rock weathering process (reproduced from Lefebvre et al. 2019).

other hand forms chemical complexes or some compounds which are electrically neutral (Manning, 2025). Depending on soil conditions, the metal and bicarbonate ions may either precipitate in the soil (as carbonates) or transfer into the ocean (as bicarbonates). In the ocean they may either remain in solution as stable bicarbonate or carbonate ions or eventually precipitate as carbonates (Beerling et al., 2018; Haque et al., 2023; Renforth and Henderson, 2017). They may also percolate through the soil into the underlying groundwater (Gastmans et al., 2016).

Rock weathering involves a series of chemical reactions which begin with the hydration of CO_2 (Eq. 1) to form carbonic acid (Lefebvre et al., 2019; Martin, 2017).

Equation (1): Hydration of CO_2

$CO_{2\,(gas)} + H_2O_{(liquid)} \rightleftarrows H_2CO_{3\,(aqueous)}$

Carbonic acid being a weak acid generally dissociates into a bicarbonate ion (HCO_3^-) and a proton (H^+). This proton then liberates the alkaline earth metal ion (e.g., Ca^{2+}, Mg^{2+}) from the silicate minerals (Eq. 2) (Haque et al., 2023).

For example, let us consider wollastonite ($CaSiO_3$); a silicate mineral used in ERW experiments and projects due to its high dissolution rate (Fig. 2.2). In case of wollastonite, the weathering reaction will be:

Equation (2): Silicate dissolution (weathering of wollastonite)

$CaSiO_{3\,(solid)} + 2H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2 + H_2O$ (Lefebvre et al. 2019)

Following this, the reaction may traverse either of two pathways. If soil conditions are favourable, the liberated metal reacts with the bicarbonate and precipitates as a metal carbonate (Eq. 3). This is the common route for silicate mineral carbonation in soil and leads to 50% of the initially sequestered CO_2 to being released back to the atmosphere and the rest remains locked in a solid form (Haque et al. 2023; Dupla et al. 2025).

Equation (3): Carbonate mineral formation (Carbonation of wollastonite)

$CaSiO_{3\,(solid)} + 2H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2 + H_2O$

$\Rightarrow Ca^{2+} + 2HCO_3^- \rightarrow CaCO_{3\,(in\ soils)} + CO_2 \uparrow + H_2O$

On the contrary, if soil conditions are not favourable, the bicarbonate and metal ions leach into groundwater or flow into streams/rivers and are eventually transported to the ocean (Eq. 4) to increase ocean alkalinity (Haque et al., 2023; Monger et al., 2015). This occurs when the pH drops below ~6-8 at surface conditions resulting in an increase of metal carbonate solubility (Haque et al. 2023).

Equation (4): Bicarbonate and metal migration from soil

$CaSiO_3 + 2CO_2 + 2H_2O \rightarrow Ca^{2+} + 2HCO_3^-{}_{\text{(to Ocean)}} + SiO_2 + H_2O$ (Lefebvre et al. 2019)

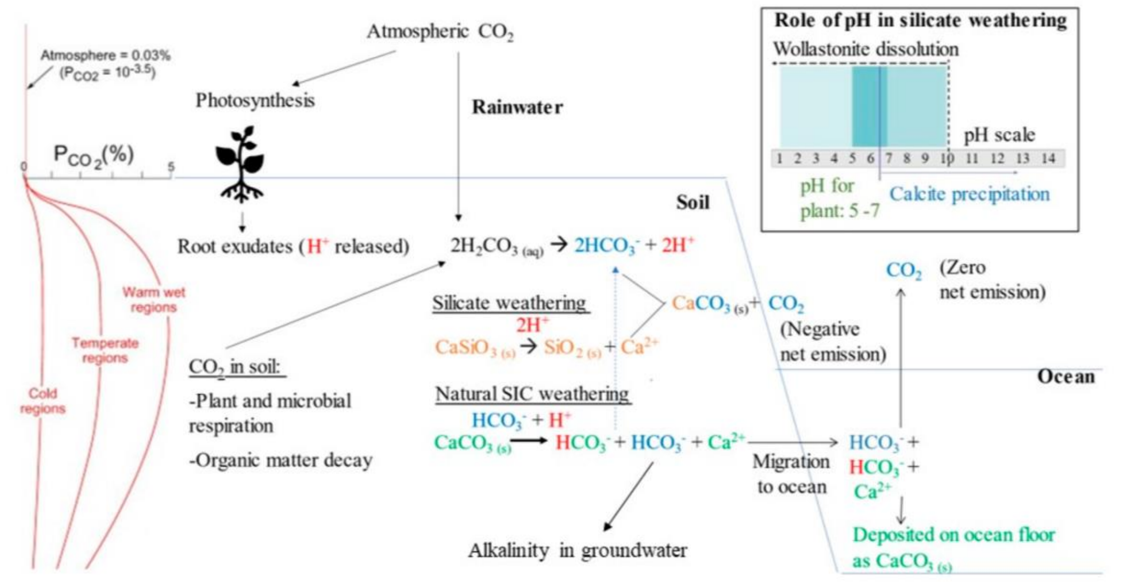
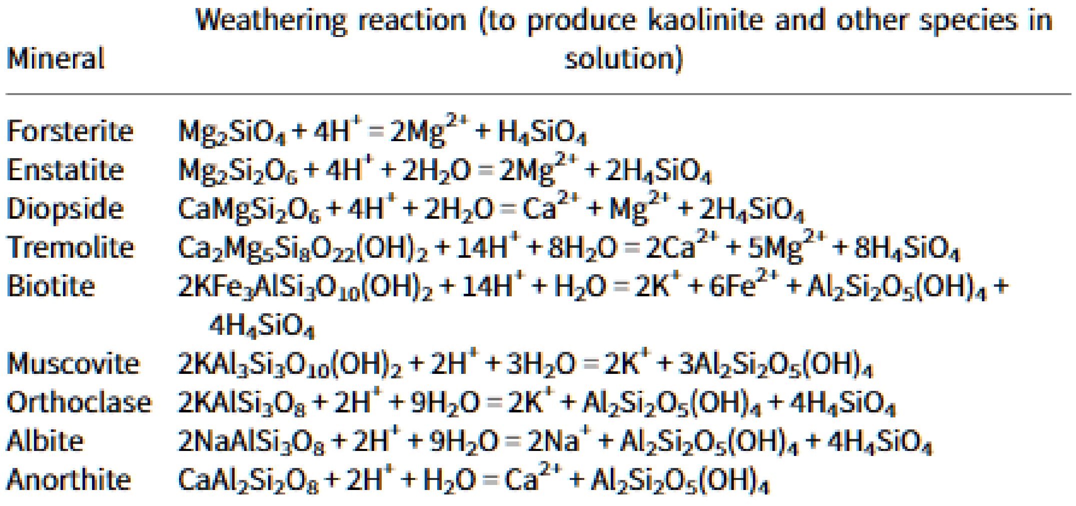


Fig. 2.2: The movement of both innate soil inorganic carbon (SIC) and pedogenic carbon (PC) is shown here with respect to wollastonite. Atmospheric CO_2 leads to an increase in the carbonic acid content of the soil system, either by reacting with rainwater or via the photosynthesis process – which exudates H^+. The H^+ ions release the base cations from the silicate minerals. These then speciate as soluble bicarbonates, and when saturated get deposited as carbonates (calcium carbonate in this case). This process leads to consumption of 2 moles of CO_2 and release of 1 mole of CO_2, resulting in net negative emissions. Excessive rainfall can also lead to transformation of PC back to soluble alkalinity in the form of bicarbonates which gets stored in groundwater, before eventually migrating to the oceans. The bicarbonates also increase alkalinity in the oceans before settling down in the ocean floors as calcium carbonates over a long period of time. Since, both silicate weathering and SIC weathering involves H^+ ions, soil pH is an important factor in the enhanced rock weathering process (reproduced from Haque et al. 2023).

The potential of each of these paths to capture carbon depends on the rock type used. The silicate dissolution reaction (Eq. 2) is the rate limiting step that controls the weathering process (Georgakopoulos et al., 2016), and is governed by reaction kinetics and mass transfer. The carbonate precipitation or dissolution reaction (Eq. 3 and Eq. 4, respectively) is controlled by thermodynamics (Zhang et al., 2020). The potential for alkaline metal ions released from silicate minerals depend on the mineral’s dissolution rate which in turn is controlled by multiple factors like temperature, soil pH, secondary precipitation, etc. (Cipolla et al., 2022; Dupla et al., 2025). The residence time of CO_2 sequestered through ERW is greater than 100,000 years depending on terrestrial or marine storage (Beerling et al. 2018).



Mineral	Weathering reaction (to produce kaolinite and other species in solution)
Forsterite	$Mg_2SiO_4 + 4H^+ = 2Mg^{2+} + H_4SiO_4$
Enstatite	$Mg_2Si_2O_6 + 4H^+ + 2H_2O = 2Mg^{2+} + 2H_4SiO_4$
Diopside	$CaMgSi_2O_6 + 4H^+ + 2H_2O = Ca^{2+} + Mg^{2+} + 2H_4SiO_4$
Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2 + 14H^+ + 8H_2O = 2Ca^{2+} + 5Mg^{2+} + 8H_4SiO_4$
Biotite	$2KFe_3AlSi_3O_{10}(OH)_2 + 14H^+ + H_2O = 2K^+ + 6Fe^{2+} + Al_2Si_2O_5(OH)_4 + 4H_4SiO_4$
Muscovite	$2KAl_3Si_3O_{10}(OH)_2 + 2H^+ + 3H_2O = 2K^+ + 3Al_2Si_2O_5(OH)_4$
Orthoclase	$2KAlSi_3O_8 + 2H^+ + 9H_2O = 2K^+ + Al_2Si_2O_5(OH)_4 + 4H_4SiO_4$
Albite	$2NaAlSi_3O_8 + 2H^+ + 9H_2O = 2Na^+ + Al_2Si_2O_5(OH)_4 + 4H_4SiO_4$
Anorthite	$CaAl_2Si_2O_8 + 2H^+ + H_2O = Ca^{2+} + Al_2Si_2O_5(OH)_4$

Table 1: Chemical reactions showing the weathering of different common rock-forming minerals. The reactions are written to have kaolinite [$Al_2(Si_2O_5)(OH)_4$] and soluble species as products (reproduced from Manning, 2022).

2.1.2. Factors affecting Enhanced Rock Weathering

The effectiveness of ERW as a CDR tool shows a large variation depending on factors such as heterogeneity in mineralogy, soil characteristics, climatic conditions, etc. A large number of geochemical, pedoclimatic and biological processes affect the weathering rates of silicate minerals and by extension, the effectiveness of ERW (Table 2 - provided at the end of this section). Here we discuss some of the major factors affecting ERW:

- **Mineralogy:** Due to the wide variety in mineral chemistry and mineral structure of silicate minerals, they show a wide range of weathering characteristics and rates of dissolution (Manning, 2022, Swoboda et al. 2022). Mineralogy also has a strong control on the carbon dioxide drawdown potential of ERW (Stubbs et al., 2022). Hence, mineralogy not only affects the quantity of CO_2 that may be captured from the atmosphere, but also the rate of weathering in surface conditions (Lewis et al., 2021). The dissolution rates of felsic rocks (e.g., granite, rhyolite) and minerals (e.g., quartz, feldspar, muscovite) tend to be lower compared to those of mafic/ultramafic rocks (e.g., basalt, peridotite) and minerals (e.g., pyroxene, olivine) (Deer et al. 2013). But even within the same mineral group, weathering rates may widely vary. The importance of specific minerals can be deduced from the fact that while K/Na- feldspars (typical in felsic rocks) and Ca-feldspars (typical in basalts), both belong to the feldspar group of minerals, their weathering rates vary widely (Deer et al., 2013; Manning, 2018). The feldspathoid group of minerals which are also framework silicates like the feldspar group of minerals, also have widely differing weathering rates. For example, both nepheline (a feldspathoid) and K-feldspars fall within the framework silicates, but the rate of dissolution of nepheline is orders of magnitude higher in spite of it containing 3-4 times less K (Manning, 2018).

  The effect of variability in mineralogy on weathering rates may be understood from the following case. In case of the minerals typically found in basalt, the weathering rates of the more abundant and fast dissolving forsterite (Mg-olivine) and Ca-plagioclase with respect to the much less abundant and slower dissolving K-feldspar vary by greater than 4 orders of magnitude, under similar pH conditions (Fig. 2.3). The amount of glass present can also add significant variation in terms of the kinetics of mineral dissolution. In case of basalt, depending on composition and soil pH, glass can weather faster than olivine (Palandri and Kharaka, 2004). This adds more variability to the rate of silicate weathering, especially in the initial stages (Lasaga, 1984). If accessory minerals are also considered, such variation in dissolution rate goes even higher (Dupla et al. 2025). Lewis et al. (2021) reported from their study, that the CO_2 sequestration potential of basalts can vary by 6-fold post 15 years of application depending on the variation in mineral chemistry of olivine and augite. This is significant as both these minerals are common in most basalts and also weather the fastest.

The amount of base cations in a rock control its ability to capture CO_2 while being used as an ERW feedstock (Dupla et al. 2025). The presence of certain elements like iron (Fe) may cause surface passivation (coating) of Mg-bearing minerals by ferric precipitates in ultramafic rocks, reducing Mg leaching -thereby reducing the rocks carbon sequestration potential (Assima et al., 2014; Vandeginste et al., 2024). Also, silicate minerals dissolve incongruently, with relatively more soluble components dissolving first (Vandeginste et al., 2024). But most studies indicate that kinetic considerations are possibly more important than the stoichiometry, with respect to the CDR potential of any particular rock type (Dupla et al., 2025; Georgakopoulos et al., 2016).

In addition to silicate minerals, lime (a common material used in current agricultural practices globally) is known to improve soil pH and also sequester carbon. But opposing views exists regarding its nature of being a carbon sink/emitter (Dietzen et al., 2018). Dissolution of lime by carbonic acid results in absorption of atmospheric CO_2, while if the dissolution is driven by stronger acids such as nitric acid (from nitrogen fertilizer dissolution or acid rain) it results in CO_2 being emitted into the atmosphere (Dietzen et al. 2018). The IPCC considers all of the lime applied during agriculture, to release CO_2 into the atmosphere. Although, the production of bicarbonate due to application acts as a temporary carbon sink, their eventual precipitation as carbonates makes this a carbon neutral process in the long term (Dietzen et al. 2018). Studies indicate that more research is needed in this regard to decide on the residence time and net carbon effect of the liming process (Dietzen et al., 2018; Hamilton et al., 2007). Moreover, some industrial alkaline waste materials like iron and steel slag, demolition waste, mine tailing from nickel, chrysotile, kimberlite and red mud mining, etc. may be used for carbonation reactions (Khudhur et al., 2022; Renforth, 2019). But due to their low concentrations of calcium (Ca) and magnesium (Mg), they have a lower CO_2 storage efficiency (Vandeginste et al. 2024).

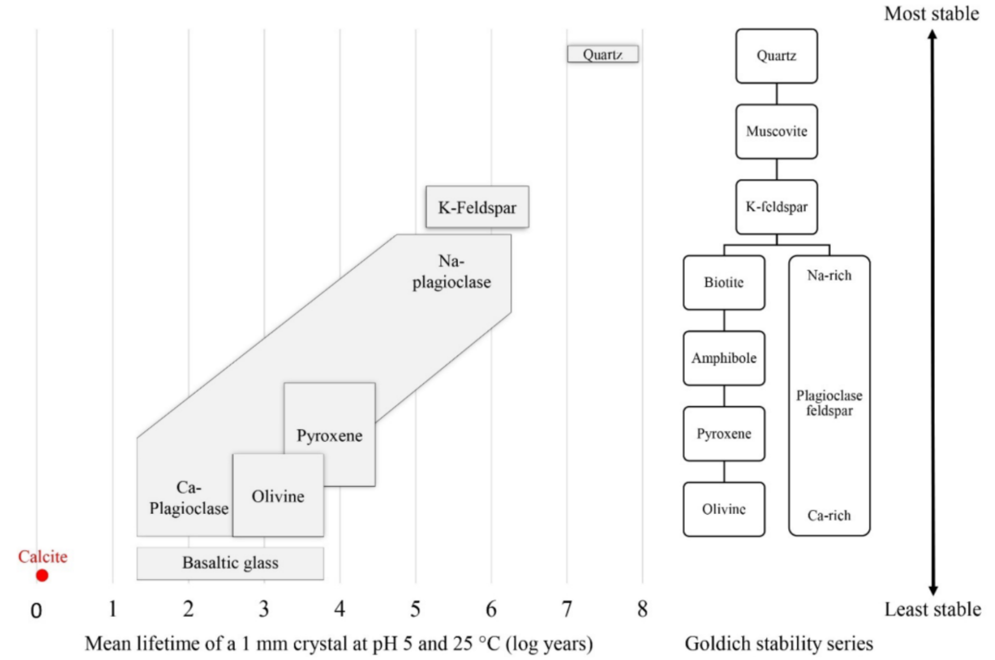


Fig. 2.3: Mean lifetime of different common basaltic minerals (left) for a crystal of size 1mm at pH 5 and temperature of 25°C. Goldich stability series (right) showing the relative stability of common rock forming minerals (reproduced from Dupla et al. 2025).

- **Grain Size and Shape:** ERW involves grinding of rocks to increase the reaction surface area to accelerate the speed of weathering by enhancing the silica dissolution reaction. Grinding of rocks into finer particles requires an idea about the particle size distribution not only to estimate the rate of dissolution, but also to find out the respirable particle size (Mills et al. 2024). As grain size decreases the value of available reaction surface area increases, showing an inverse relationship. Laboratory experiments generally show that below 100µm there is a rapid increase in amount of reaction surface area, and thereby increased reactivity (Brantley and Mellott, 2000). Both experimental (Amann et al., 2020; Gillman, 1980) and modelling (Beerling et al., 2018; Moosdorf et al., 2014) studies indicate the positive effect of grain size reduction on the mineral dissolution kinetics (Fig. 2.4). Some have even suggested grain size lower than 10 microns for ERW to be effective for CDR (Rinder and von Hagke, 2021). In spite of this direct relationship, the energy cost of producing even finer particles damages the CDR efficiency of any rock (Rinder & von Hagke, 2021), in addition to other environmental challenges. Also, recent research suggests, that the relationship between grain size and reaction kinetics is more complex than originally thought (Dupla et al. 2025). For example, most models on mineral dissolution consider an ideal scenario of shrinking core and do not account for changes in the shape of grain surface as dissolution continues (Strefler et al., 2018).

The shape of mineral grains also plays an important part in addition to particle size. Fibrous minerals (like serpentine, etc.) generally tend to react faster due to their higher surface area to volume ratio (Kelemen et al., 2020). The crystal structure of phyllosilicates like biotite, tends to support faster dissolution rates compared to framework silicates like feldspars (Mohammed et al., 2014). Since, mineral dissolution is affected by crystal defects and other imperfections, the relationship between the rate of mineral dissolution and surface area of the particles becomes more complicated (Vandeginste et al., 2024). It is understood that weathering does not affect mineral grains equally, instead, they concentrate on zones of crystal defects. Therefore, grinding rocks to powders may increase the specific surface area of the grains, the actual reactive surface area may vary (Swoboda et al., 2022).

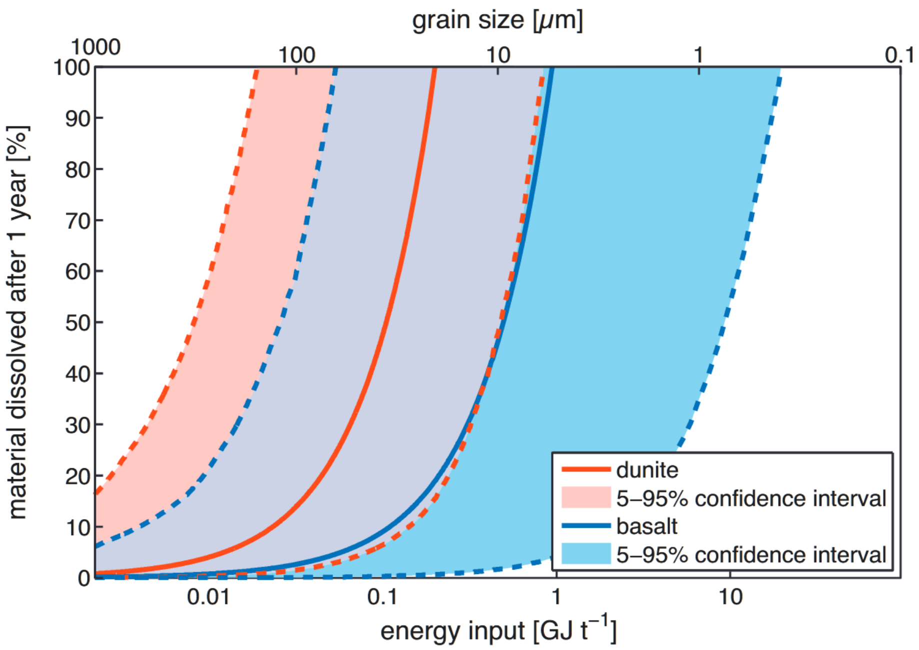


Fig. 2.4: Graph showing the relationship between rate of dissolution and grain size, along with the energy input required to produce the respective grain size (reproduced from Strefler et al. 2018)

- **Temperature:** While lower temperatures favour more CO_2 dissolution in water, higher temperature favours faster mineral dissolution (Vandeginste et al., 2024).

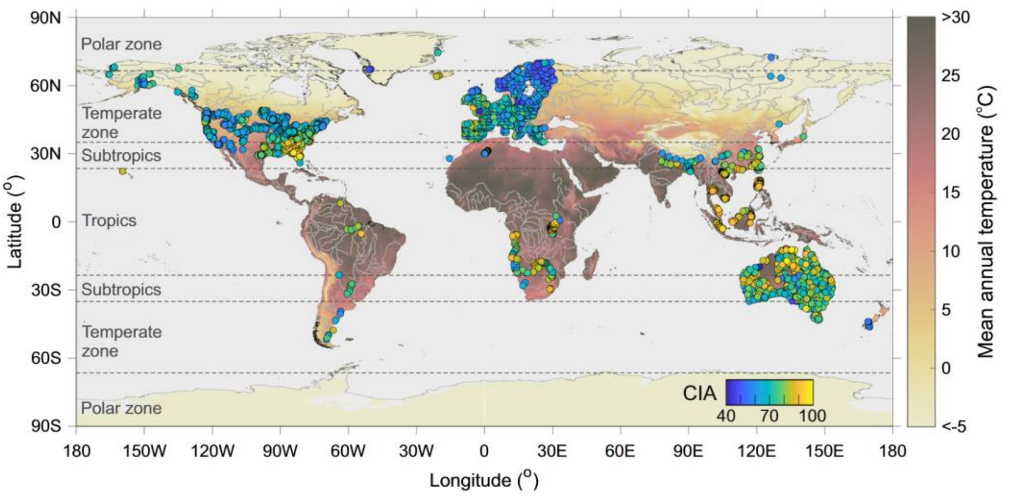


Fig. 2.5: Map showing the chemical index of alteration (CIA) across the world. Also shown is the mean annual temperature. Note the higher value of CIA in the tropics and subtropics compared to temperate and polar zones (reproduced from Deng et al. 2022).

The dependence of silicate weathering rates on temperature is well studied both in lab-conditions and in catchments with silicate lithologies (Brantley et al., 2023; Deng et al., 2022). Provided neither fresh supply of mineral nor water are a limiting criterion, weathering rates generally increase exponentially with temperature (Li et al., 2016)). For example, the difference in weathering rates of olivine at 4°C and 19°C is of the order of two magnitudes (Pogge von Strandmann et al., 2022). However, the influence of temperature also depends on the field conditions (Fig. 2.5). For example, although higher temperatures favour faster weathering, they can also cause faster evaporation affecting soil moisture, thus affecting weathering rates (Dupla et al. 2025). Some studies also suggest that evaporation leads to higher rate of carbonation due to the increase in salinity of water and capillary action driving fluid from below towards the dry surface (Power et al., 2014; Wilson et al., 2014). The ambient temperature and difference between ambient temperature and soil temperature can also impact the process of ERW. Higher difference between ambient and soil temperatures control CO_2 entering into the soil, by favouring more CO_2 ingress with higher ambient temperatures (Nowamooz et al., 2018).

- **pH:** Possibly the most prominent control on ERW rates is pH. Most studies indicate that silicate weathering rates decrease with increasing pH or might follow a U-shaped curve, with neutral conditions showing the least amount of weathering (Fig.

2.6). It is generally understood that acidic conditions ($pH<6$) favour mineral dissolution; although occasionally alkaline conditions ($pH>9$) can also increase mineral weathering (White & Brantley, 2018; Dupla et al., 2025). Research suggests, aluminium free minerals such as olivine and wollastonite dissolve faster in acidic soils, whereas, if we consider anorthite (Ca-rich end member of feldspar), the rate of dissolution at pH 3 and pH 10 is two orders of magnitude higher compared to the rate of dissolution at pH 7 (Appelo and Postma, 2010). In case of acidic conditions, the metal cations are removed from the silicate structure by protons which drives the weathering process; while in alkaline conditions the process is driven by the detachment of silica oxyanions which are negatively charged (Brady and Walther, 1989).

From the perspective of basic chemistry, ERW is an acid hydrolysis process where a proton removes a metal cation from the silicate structure. The protons that lead to acid hydrolysis of the silicate minerals can be generated through a variety of pathways (Dupla et al. 2025). These maybe: (a) from the dissolution of CO_2 (atmospheric CO_2) in rain (b) dissolution of CO_2 derived from aerobic respiration of microbes and plant roots into soil pore water (c) oxidation and dissolution of sulphur and nitrogen into atmospheric water to form sulphuric and nitric acids (d) formation of sulphuric acid from trace amounts of sulphides contained in rocks such as basalts or from fertilizers (e) proton released by the oxidation of ammonia in ammonia-based fertilizers (f) mineralization of organic acids. If this removal of cation is driven by carbonic acid, the proton consumption automatically leads to CO_2 sequestration. But if this process is driven by some other acid, no direct CO_2 sequestration takes place (Dupla et al. 2025). Commonly, H_2CO_3 activity during ERW is dependent on soil pH and partial pressure of CO_2 (Lal, 2017). The acid dissociation constant for carbonic acid decreases fast below pH 6.4 (Dupla et al. 2025). Research suggests, that less than 25% of all protons present for silicate weathering are supplied by carbonic acid at pH 5.2 (Dietzen and Rosing, 2023). At such low pH, silicate weathering is driven by other acids (like sulfuric and nitric acids) and as such, no CO_2 sequestration takes place (Dupla et al. 2025).

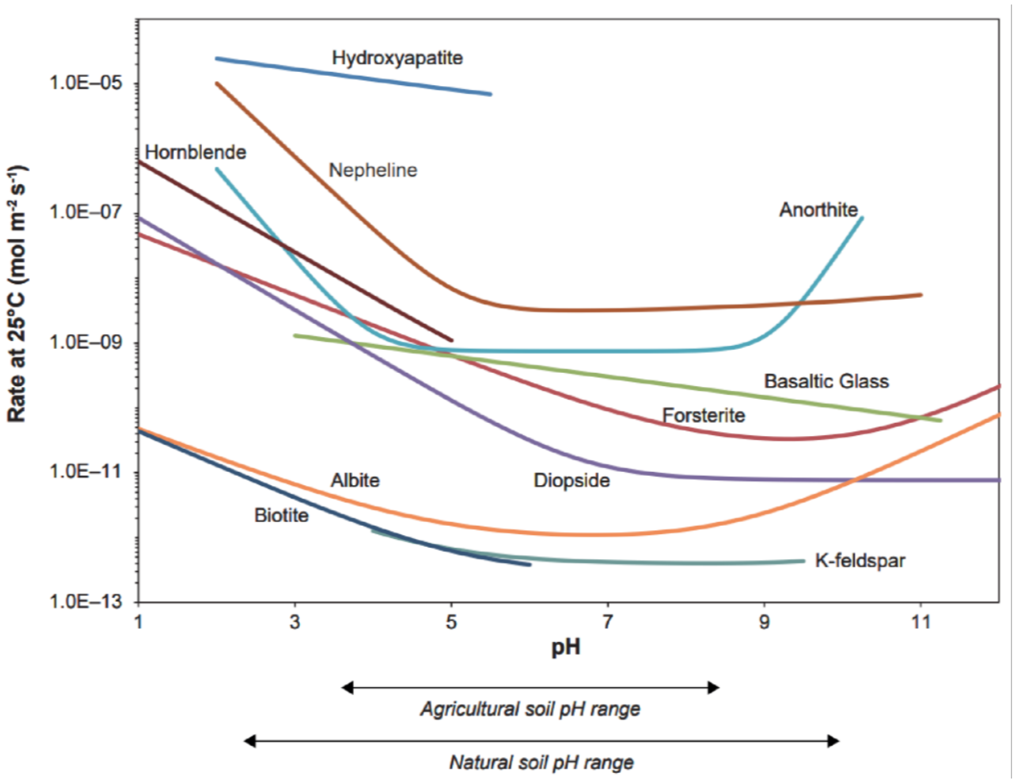


Fig. 2.6: Figure showing the relationship between the rate of weathering at 25°C vs soil pH. (reproduced from Dupla et al. 2025)

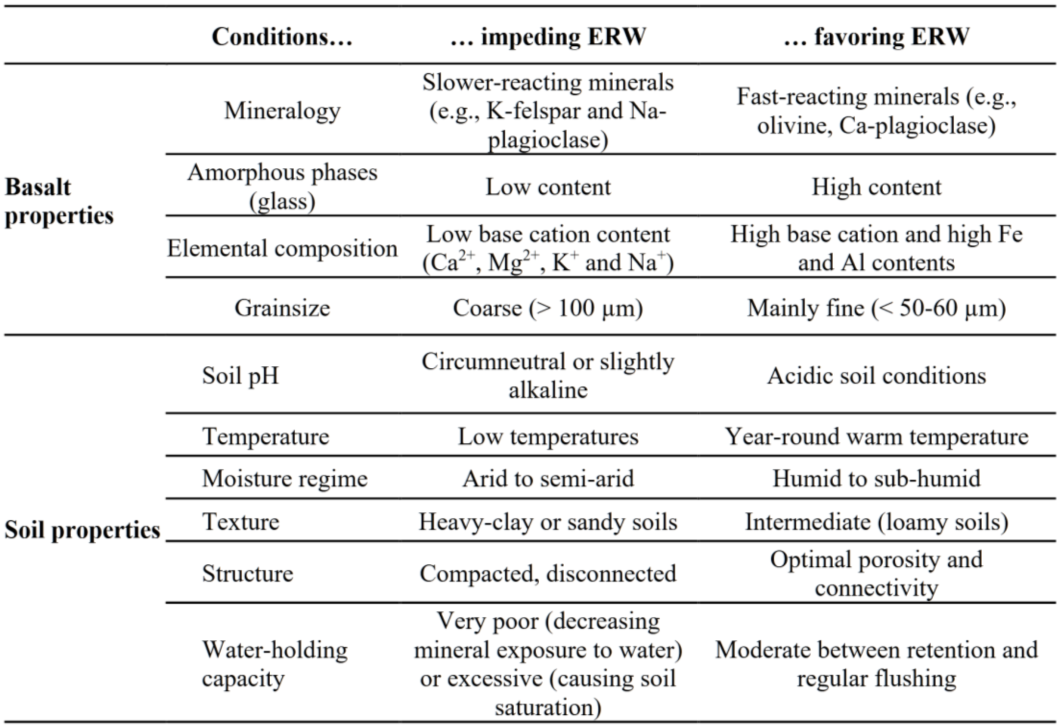
- **Saturation conditions:** The efficacy of ERW depends on the rate of weathering which is governed by Eq. (2), which is essentially a dissolution reaction. Therefore, any factor influencing solubility and the concentration of solute during weathering will causally affect ERW rates. If no secondary precipitation or removal of the dissolved silicate minerals take place, the concentration of products (see Eq. 2) increases and thereby, reduces ERW rates (Dupla et al. 2025). Considering that most soil solutions are already near saturation in terms of the primary elements derived from silicate weathering, saturation conditions become a pivotal criterion to evaluate ERW effectivity (White and Brantley, 2018).

  Soils with high clay content and compacted soil features (like soil crusting on the surface, higher overall compaction, etc.) limit porosity and permeability (de Lima et al., 2022). This affects the drainage of soil solution resulting in the system reaching thermodynamic saturation faster. On the contrary, sandy soils typically do not retain water well, as a result, the time required for dissolution reactions to take place between minerals and soil pore water is reduced significantly (Dupla et al., 2025; Smettem and Gregory, 1996). Therefore, a balance needs to be maintained considering the climatic and hydrological conditions (Dupla et al. 2025).

- **Secondary precipitation:** During the initial stages of weathering the rate of dissolution is high as the loosely bonded ions, highly reactive phases and surfaces, etc. rapidly dissolve (Paulo et al., 2021; Stubbs et al., 2022). 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 (Schaef et al., 2009; White and Brantley, 2003). Such precipitates can take the form of coatings or nodules or even cemented carbonate layers. This is one of the main mechanisms through which the dilution of the soil solution can be maintained resulting in preservation of far-from-equilibrium conditions (Dupla et al. 2025). Conversely, many studies suggest that secondary precipitation can lead to a reduction in weathering rates by coating of the silicate minerals that are supposed to undergo dissolution (Cailleteau et al., 2008). Currently, it is understood that the level of coating or passivation of the silicate minerals primarily depends on the extent of passivation and the crystallographic similarities between the silicate minerals and the secondary precipitates (Nugent et al., 1998; Putnis, 2009). While some studies reported no impact of secondary precipitation on ERW rates, others reported an increase inferring that this was caused due to maintenance of far-from-equilibrium conditions (Daval et al., 2009; Murakami et al., 1998). In the case of ERW, secondary carbonates are the most likely candidates for secondary precipitation. The effect of secondary weathering on weathering rates is still disputed (P. C. Bennett, 2001; Stockmann et al., 2011). Also, secondary precipitation can often prove as a hindrance to gas and water movement in soil column experiments.
- **Climate:** Climate and weather are prime factors that control the rate of enhanced rock weathering (Abdalqadir et al., 2024). Mineral dissolution kinetics is generally favoured in warmer climates improving the CO_2 sequestration capabilities of enhanced rock weathering (Hartmann et al., 2013; Taylor et al., 2016). These observations are also validated experimentally where higher temperatures are shown to have orders of magnitude faster dissolution rates for the same mineral compared to lower temperatures (Pogge von Strandmann et al., 2022). Studies suggest that CO_2 sequestration by ERW will be less efficient in temperate zones compared to warmer climates (Abdalqadir et al. 2024). Additionally, humidity and

the amount of precipitation also strongly affect the process of ERW. With increased rainfall the hydrolysis reactions involved in rock weathering also increases, thereby improving ERW (Dietzen et al., 2018). Under dry climates, weathering processes are drastically slowed down due to an absence of available moisture that affects the kinetics of mineral dissolution reactions (Renforth et al., 2015).

In addition to climatic variations, seasonal changes in the weather are also known to affect ERW. Rocks undergoing freeze-thaw cycles in temperate zones mechanically break, causing an increase in reaction surface area, thus increasing rate of rock weathering (Kelland et al., 2020). Also, extreme weather events like droughts and floods are known to result in decreased or increased rock weathering. The change in soil pH and cation availability caused by such events directly affects ERW (Strefler et al. 2018). In case of floods or heavy rains, soil fertility may be affected by the leaching of nutrients available, thus influencing ERW (Wood et al., 2023). Studies like Berge et al., (2012) and Haque et al. (2020) suggest that even microclimatic variations caused by different agricultural practices affect the effectiveness of ERW, by changing parameters such as soil temperature, moisture and biological activity (Te Pas et al., 2023). Moreover, as climate change leads to changing weather, climate and precipitation patterns; ERW rates are expected to be affected significantly (Vanderkloot and Ryan, 2023).



	Conditions…	… impeding ERW	… favoring ERW
Basalt properties	Mineralogy	Slower-reacting minerals (e.g., K-felspar and Na-plagioclase)	Fast-reacting minerals (e.g., olivine, Ca-plagioclase)
	Amorphous phases (glass)	Low content	High content
	Elemental composition	Low base cation content (Ca^{2+}, Mg^{2+}, K^+ and Na^+)	High base cation and high Fe and Al contents
	Grainsize	Coarse (> 100 µm)	Mainly fine (< 50-60 µm)
Soil properties	Soil pH	Circumneutral or slightly alkaline	Acidic soil conditions
	Temperature	Low temperatures	Year-round warm temperature
	Moisture regime	Arid to semi-arid	Humid to sub-humid
	Texture	Heavy-clay or sandy soils	Intermediate (loamy soils)
	Structure	Compacted, disconnected	Optimal porosity and connectivity
	Water-holding capacity	Very poor (decreasing mineral exposure to water) or excessive (causing soil saturation)	Moderate between retention and regular flushing

Table 2: Rock and soil geochemical properties controlling ERW efficacy (reproduced from Dupla et al. 2025)

- **Plants:** Studies suggest that roots of plants can induce physicochemical conditions that favour silicate weathering (Hinsinger et al., 2001; Vicca et al., 2022). (Haque et al., 2020) conducted a microplot study across planted and unplanted soils mixed with silicate rock dust to measure carbon sequestration, and reported a 10 times higher sequestration in the planted soils. The absorption of elements like silicon (Si), magnesium (Mg), calcium (Ca) and iron (Fe) by roots helps avoid pore water saturation, thereby preventing decrease in weathering rates (Harley and Gilkes, 2000; Hinsinger, 1998). Plant roots release protons and CO_2, which result in a decrease in pH and increase in CO_2 concentration around the roots (Lenzewski et al., 2018). As a consequence, they stimulate silicate weathering (Harley and Gilkes, 2000). Also, plants secrete organic compounds that help in chelating reaction products and dissolving silicate minerals even at near neutral pH (Dontsova et al., 2020; Harley and Gilkes, 2000; Zhang and Bloom, 1999). Research suggests that the control of plants on silicate weathering varies, at least in part due to the different nutrient absorption strategy of different plants (Vicca et al. 2022). For example, weathering rates of wollastonite were higher in case of leguminous beans compared to non-leguminous corn (Haque et al., 2019).

- **Soil Enzymes:** 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; Zaharescu et al., 2020). Carbonic anhydrases (CA), an enzyme vital to plant respiration, CO_2 transport and photosynthesis, is known to favour silicate weathering and precipitation of carbonates (Xiao et al., 2015; Zaihua, 2001). CA acts as a catalyst in the equilibrium between CO_2 and bicarbonate, doing 10^6 CO_2 conversions every second (Vicca et al. 2022). A heightened expression of CA genes in microbes facilitates carbonic acid generation and a subsequent increase in silicate weathering rates. Urease, a nickel (Ni) metalloenzyme, which catalyzes the urea → ammonia reaction can also raise pH and improve the rate of carbonate precipitation (Vicca et al. 2022). Recent research suggests, soil treated with urease increases carbonate precipitation with the added effect of decreasing heavy metal concentration in soils (Moghal et al., 2020).
- **Microbes:** Studies indicate that mycorrhizal fungi have substantially increased dissolution of minerals at evolutionary time scales(Zaharescu et al., 2020). Experiments also report an increase in rate of silicate weathering when such fungi are involved (Bonneville et al., 2011; Burghelea et al., 2018). (Wild et al., 2021) reported a 10-fold increase in mineral dissolution across individual fungi filaments compared to areas with no fungi. This increase is driven by the protons, organic acids and chelators released by fungi (Van Hees et al., 2006). They create elemental gradients away from minerals and can also act as sinks for weathered products, facilitating mineral dissolution (Oelkers et al., 2015; Van Hees et al., 2006). (Xiao et al., 2012) suggests that exposing fungi to minerals may stimulate genetic pathways related to the conversion of CO_2 to carbonates. There is probably a dependence between specific fungi species and the chemistry of applied rock powder (Vicca et al. 2022).

  In addition to fungi, other microorganisms like bacteria can also quicken silicate weathering (Gouda et al., 2018). The improvement in silicate weathering due to microorganisms is in large part due to the release of organic acids and dissolved CO_2, that can reduce the pH to as low as 2.3 (Ahmed and Holmström, 2014). Studies have shown the potential of potassium solubilizing bacteria in enhancing the release of K^+ from muscovite mica (one of the slowest weathering minerals) (Basak and Biswas, 2009; Rani et al., 2025). Moreover, both fungi and bacteria also release chelates and enzymes that can reportedly speed up mineral dissolution up to 100-fold (Sun et al., 2013; Xiao et al., 2015). Some chelates like siderophores are element specific, as such, their production is driven by the rock type used and characteristics of the soil (Vicca et al. 2022).

- **Macro-invertebrates:** Earthworms affect both the physicochemical properties and biological parameters in soil through activities such as burrowing and feeding (Blouin et al., 2013). They are known to increase nutrient availability in addition to increasing mineral dissolution (Van Groenigen et al., 2019). In a recent set of experiments, (de Souza et al., 2013; Paula De Souza et al., 2018; Souza et al., 2019) used gneiss and steatite in vermicompost containing earthworms. Their results show an increase in rock weathering and nutrient release, although, the results were statistically significant only for steatite (de Souza et al., 2013). Research has shown that a large amount of inorganic carbon (C) is sequestered as calcium carbonate in the calciferous glands of earthworms (Briones et al., 2008; Lambkin et al., 2011; Versteegh et al., 2014). Depending on the mineral used, worms can also help in mineral weathering by releasing specific microbes and stimulating microbial activities (Carpenter et al., 2007; Liu et al., 2011). Lastly, earthworms can help by better distributing the silicate grains in the soil profile (Vicca et al. 2022). Similar to earthworms, even ants are known to improve biogeochemical cycling and mineral weathering (Dorn, 2014; Viles et al., 2021). Studies indicate that organic acids like formic acid, released by ants stimulate silicate rock weathering (Viles et al., 2021). However, more research is needed to understand their influence on rock weathering; a 25-year long experiment shows 60-330 times higher mineral dissolution rates for olivine and plagioclase (Dorn, 2014).

2.1.3. Potential for CDR

Rock weathering removes ~1.1 Gt CO_2 per year naturally (Strefler et al. 2018). The CDR potential of ERW derives from the fact that CO_2 is removed from the atmosphere and stored as bicarbonates, which then either precipitates or drains. When drained, they either percolate into the ground water system while some runs off as surface water. Ultimately, this drainage finds its way into the ocean where they are stored over periods higher than

100,000 years (Beerling et al., 2020; Haque et al., 2019). When precipitated as soil carbonates the CO_2 sequestration efficiency reduces by 50% (Haque et al., 2023; Lefebvre et al., 2019). Recently, modelling of the CDR potential from ERW of nations across the world suggests China, USA and India to be the top three candidates (Beerling et al. 2020). Beerling et al. (2020) estimate a CDR potential of 25-100 Gt CO_2 over the next 5 decades. But other global estimates of ERW's potential to remove carbon dioxide range from ~3.7 Gt CO_2 per year – equivalent to >300 Gt CO_2 in the 21st century (Köhler et al., 2010), to as high as 5500 Gt CO_2 being removed during the 21st century (Taylor et al., 2016). The experimental evidence that upholds the idea of artificially-enhanced weathering is from Iceland (Manning, 2025). (Moulton, 2000) showed that water being drained through weathering basalt in woodlands contain up to 12kg C per hectare in the form of bicarbonates. Estimates by (Dessert et al., 2003) indicate that annually 4.08×10^{12} mol CO_2 flow into the ocean by normal basalt weathering, which is the most used rock for ERW experiments and projects.

The amount of CO_2 that maybe removed through ERW is generally estimated by applying a modified version of the 'Steinour' formula (Renforth, 2019). A simplified version of this equation for basaltic rocks is:

$$erwCO_2 = \frac{44}{100} \times (\frac{CaO}{56} + \frac{MgO}{40} + \frac{Na_2O}{62} + \frac{K_2O}{94} - \frac{SO_3}{80} - \frac{P_2O_5}{142}) \times 10^3 \times 1.5$$

Using this equation, the potential for CDR of basaltic rocks is generally estimated to be 230-250 kg CO_2 per tonne of rock (Manning et al., 2024), and occasionally even up to 300 kg per tonne (Renforth, 2019). The potential for removing CO_2 is even higher for some other rocks such as dunite, with estimates putting their sequestration potential at ~95 Gt CO_2/year (Strefler et al. 2018).

If properly implemented, ERW has the potential to sequester gigatonnes of CO_2 annually, contributing significantly to global climate goals (Almaraz et al., 2022; Goll et al., 2021) (*see Table 3* for some estimates of CO_2 sequestration from experimental studies). In a recent study, Renforth (2019) estimates an annual CO_2 sequestration of 2.9-8.5 gigatonnes from non-hazardous materials formed as a by-product of industrial processes.

Material	**Scale**	**Plant Presence**	**Dosage (t/ha)**	**CO_2 Capture Metric**	**Tonne CO_2/ha/yr**	**Reference**
Basalt	Mesocosm	Yes	100	Mg balance	3.01	(Kelland et al., 2020)
Concrete	Field	No	Not stated	SIC	85	(Washbourne et al., 2015)
Dolerite	Field	Yes	Not Stated	SIC	17.6	(Manning et al., 2013)
Olivine	Pot	Yes	204	Mg balance	2.69	(Berge et al., 2012)
Olivine	Mesocosm	Yes	220	Mg balance	0.05	(Amann et al., 2020)
Olivine	Column	No	50	Mg balance	4.16	(Dietzen et al., 2018)
Olivine	Column	No	127	Mg balance	0.30	(Pogge von Strandmann et al., 2022)
Wollastonite	Pot	Yes	221	SIC	39.3	(Haque et al., 2019)
Wollastonite	Field	Yes	1.25-5.0	SIC	0.28-2.4	(Haque et al., 2020)
Wollastonite	Watershed	Yes	3.44	Ca balance	0.77	(Taylor et al., 2021)
Wollastonite	Column	No	221	Si, Ca, HCO_3^-	24.5-52.9	(Wood et al., 2023)

Table 3: Some estimates of CO_2 removal rates by ERW, as calculated in various soil studies (reproduced from Vandeginste et al. 2024).

2.2. Policy Review

2.2.1. Overview

Climate policy has taken a long journey from Kyoto protocol in 1997 to COP30. Given below is a roadmap from Kyoto protocol to COP30:

A Roadmap from Kyoto Protocol (1997) to COP30

1997 – Kyoto Protocol (KP): Formal introduction of carbon markets through flexibility mechanisms like the Clean Development Mechanism (CDM) and Joint Implementation (JI).

2005 – KP enters into force: Active implementation of carbon trading and credit mechanisms across participating countries.

2015 – Paris Agreement: Establishes a global commitment to limit warming to well below 2°C and introduces provisions for international carbon trading under Article 6.

2021 – Glasgow (COP26): Operational rules for Article 6 adopted, paving the way for standardized carbon markets and credit accounting.

2022 – Sharm El-Sheikh (COP27): Recognition of CDR as an essential element for net-zero pathways; renewed focus on integrity in voluntary carbon markets.

2023 – Dubai (COP28): Increasing alignment between national decarbonization plans and emerging CDR technologies; emphasis on private sector financing.

2025 – Belém (COP30): The latest Conference of Parties ended with countries agreeing to transition to stronger financing of climate mitigation, accepting Just Transition Measures (JTM) and prioritising cooperation and implementation through the Global Mutirão Agreement.

The project “Climate Action Tracker” (CAT.org; Internet Archive) tracks and evaluates the targets and policies pursued by different countries with respect to the 1.5°C temperature limit set by the Paris Agreement. Their data from July, 2025 classifies all the major greenhouse gas emitting countries (like China, USA, India, EU, Russia, etc.) as having climate policies which are ‘insufficient’, ‘highly insufficient’ or ‘critically insufficient’ with respect to achieving the targets set in the Paris Agreement. Some of the smaller countries like Bhutan, Nepal, Norway, Nigeria, Costa Rica, Ethiopia, etc., have climate policies which are ‘almost sufficient’ with respect to the 1.5°C target of the Paris Agreement. Unfortunately, none of the countries studied (covering ~85% of global greenhouse gas emissions, ~ 70% of global population) have policies that are ‘totally sufficient’ to be compatible with the 1.5°C temperature target set in the Paris Agreement.

The use of CDR technologies on a large scale for climate change mitigation has been debated from the late 1990's (Obersteiner et al., 2001; Williams, 1998). Recently, there is a growing consensus in climate science and climate policy debates that only reducing emission of greenhouse gases will not suffice to reach the Paris Agreement goal of keeping rise in global average temperatures well below 2°C compared to pre-industrial era (Schenuit et al., 2025). There is also a growing demand from developing countries such as India, that developed countries need to reach net negative emissions, so as to free up the carbon budget for equitable redistribution based on the core principle of fairness (Mohan et al., 2021). Application of CDR (including ERW) methodologies to achieve net-zero CO_2 and possibly also net-negative emissions is inevitable (Intergovernmental Panel On Climate Change (IPCC), 2023). The difference in the maturity levels of the various CDR pathways is reflected by the volume of scientific literature covering them (Dörpmund, 2025; Prütz et al., 2023).

In this context, studies show there is a general lack of regulation and innovation to facilitate scaling up of CDR technologies like ERW in developing countries such as India, Brazil and China, as is also the case with Organisation for Economic Co-operation and Development (OECD) countries (Schenuit et al. 2025). Researchers suggest repurposing current policy instruments, specially from the Land Use, Land Use Change, Forestry (LULUCF) sector for CDR policy and innovation (Schenuit et al., 2025). This is truer for countries like India, Brazil and China where LULUCF-related regulations are currently at a much higher level compared to those for carbon capture and storage-based CDR methodologies. Here, we compare the current state of policy framework and level of innovation in CDR methodologies in general and ERW in specific; across India, Brazil, China and other OECD countries. Since, CDR or ERW exist within the broader ambit of climate change policy and carbon markets, we also focus on any other relevant CCU/S or carbon market related policy, wherever necessary.

2.2.2. Brazil:

From the early days of discussions on climate change, Brazil has been considered as a key factor in influencing global climate (Franchini and Viola, 2019). This importance stems from the fact that a large part of the Amazon rainforest lies within Brazil. So, any deforestation in those areas raises climate risks while any reforestation or afforestation efforts have direct impact on climate change mitigation (Rochedo et al., 2018).

Although not related to ERW, the use of silicate rock powders to substitute for potassium fertilizers and supply soil with potassium and other nutrients has been studied from the 1970's and 1980's in Brazil (Ramos et al., 2022). Brazilian law (12890/2013) considers silicate rock powders as 'remineralizers', a category of materials to be used as an input in agriculture. Therefore, laws involving aspects of their safety, production and use are covered, as they are considered to be fertilizers (Brazil, 2013). The Ministry of Agriculture, Livestock and Supply (MAPA) on March 10, 2016 published Normative Instructions (NI no.5) which establishes the specifications based on which such rock powders maybe used. These rules mandated the use of geochemical and mineralogical analyses to prove the safety of such remineralizers. Chemical analyses to show the sum of bases ($CaO + MgO + K_2O$), maximum percentage of potentially toxic elements (As, Hg, Pb, among others), etc., are now required. Additionally, this law also considers other factors like pH of abrasion, free silica content and granulometry of the materials. The use of powdered silicate rocks ideally requires peer-reviewed publications to show its effectiveness and must be registered in Brazil (Manning, 2025, 2022; Ramos et al., 2022), though this is not related to ERW policy.

Currently, the role of LULUCF as a CDR approach has become less specific in the latest Nationally Determined Contributions (NDC) (den Elzen et al., 2022). In spite of this, the level of policy and regulation for carbon capture and storage-based CDR methodologies including ERW remains much lower. The discussion on CDR technologies like ERW is still limited to expert circles (Machado et al., 2021). Although, in the state of Santa Catarina the coal industry runs a research institution that focuses on understanding and investing on CCS technologies; the country lacks a policy framework to facilitate large scale CDR technologies (Machado et al. 2021).

Compared to the LULUCF sector the level of innovation also remains low in the CDR sector. No substantive research, development or demonstration project is pursued in terms of Bioenergy with Carbon Capture and Storage (BECCS) or Direct Air Capture and Carbon Storage (DACCS) technologies. Although, some demonstration projects and experimental DAC plants are being announced (Bioenergy International, 2021; Repsol Sinopec, 2022, 2023). Recently, scientists have indicated large potentials for biochar and ERW in Brazil going in the future (Goll et al., 2021; Latawiec et al., 2019).

2.2.3. China:

China is attempting to place itself as the 'Climate leader for the Global South' (Qi and Dauvergne, 2022) and focusing on repurposing climate policy related to LULUCF sectors for CDR policymaking (Mal et al. 2024). This seems logical as the level of regulation related to LULUCF-based CDR is already high in the country. CDR methodologies related to carbon capture and storage (CCS) are getting more attention among expert communities and are now considered for national-level climate modelling (He et al., 2022; Jiang et al., 2020). Although, dedicated policies for CDR are still non-existent, the government is facilitating R&D and application of CCUS-based (Carbon Capture Utilization and Storage) CDR projects through pilot projects in its 14th Five Year Plan (Jiang et al. 2020). But most of these studies are linked to projects like Enhanced Oil recovery (EOR) and not ERW. Although, multiple academic studies on ERW are being funded by China through agencies at both national and regional levels (Chen et al., 2026).

Similar to Brazil, the level of innovation is much higher in LULUCF compared to CDR. In spite of no known funds specially for CCS-based CDR, DACCS and BECCS appears to be getting more attention (Liu et al., 2022). (Kang et al., 2022) analysed patents related to CDR and found that after US, China holds the most CDR-related patents mostly focusing on BECCS, biochar, DAC and soil carbon management. Also, multiple start-ups like 'Carbon Infinity' and 'C4X' are competing at a global scale (Izikowitz, 2021).

2.2.4. India:

India is the third largest emitter and as such is starting to play an important role in global climate negotiations over the last decade (Mohan, 2017). In view of the depleting carbon budget for India, the government has prioritised climate change as a national political agenda (Dubash, 2019) and urged developed nations to pursue 'net-negative' pathways so as to free up 'carbon space' for developing countries such as India (Mohan et al. 2017). As is the case for Brazil and China, the level of regulation on LULUCF sector and LULUCF-based CDR is high in India compared to other CCS-based CDR methodologies. Forest restoration is an essential part of the government structure. India is generally considered to have strong interest in CCS-based CDR. This interest is due to India's high potential for CO_2 sequestration and its large fleet of coal power plants, both of which are currently under active research (Bakshi et al. 2023; NITI Aayog, 2022). But most of this research is concentrated on injecting CO_2 in geological rock formations either for storage or EOR (NITI Aayog, 2022) and not ERW. In spite of such interest, the level of regulation remains low and no major demonstration plants are in operation (Schenuit et al., 2025). Authors have identified a 'lack of policy ecosystem' for CCUS (Malyan & Chaturvedi, 2021). CDR technologies are gaining traction and perceived to be receiving more support (Vishal et al., 2021). But recent initiatives do not focus on CDR technologies like ERW, rather they are strongly focused on CCU and/or CCS to reduce fossil fuel emissions (Shaw and Mukherjee, 2022).

With regards to innovation, India similar to Brazil and China have a well-established LULUCF-based CDR market. But strong criticisms and concerns about the integrity for credits generated and traded exist, along with concerns over their incentives (Fleischman et al., 2021). The level of CDR-based innovation is low compared to LULUCF-based sector; though, Indian industries and public sector undertakings are trying to develop CCS capabilities and facilities (Schenuit et al. 2025). In spite of all these efforts, the number of domestic demonstration projects is limited (Vishal et al., 2021). Recently, research efforts are being increased as the government joined the Accelerating CCUS Technologies initiative under Mission Innovation (MI) and has founded two 'National Centres of Excellence in Carbon Capture & Utilization'. Field studies such as carbon capture and EOR in Gujrat by Institute of Reservoir Studies and CO_2 storage in basalt formations by National Geophysical Research Institute, Hyderabad are being conducted. But none of these efforts are usually in direct reference to CDR or ERW (Schenuit et al., 2025). India adopted the Carbon Credit Trading Scheme in July, 2024; enabling its journey towards a rate-based Emissions Trading System (ETS) (PIB-GoI, June 2025). India's Ministry of Power currently recognises and approves crediting methodologies such as renewable energy, mangrove afforestation and reforestation, landfill methane recovery, etc., but does not recognise ERW (PIB-GoI, March 2025). Recently, India finalised the National Designated Authority and is enroute to enabling a carbon trading regime (Aug, 2025 – The Hindu; PIB-GoI, June 2025).

2.2.5. USA:

The U.S. government policy on Enhanced Rock Weathering (ERW) is currently in a developmental and research-support phase. Federal agencies including the U.S. Department of Agriculture (USDA) through its Partnerships for Climate Smart Commodities program, and the Department of Energy (DOE) under its Carbon Negative

Shot initiative, have begun funding projects to scale ERW (DOE, 2020). These projects focus on research to evaluate ERW's effects on crop productivity, soil health, atmospheric CO_2 reduction, ecosystems, and ocean acidity. ERW is recognized as a carbon removal technology by the DOE within its pilot procurement plan, although no federal purchase agreements are yet in place. USA is also supporting CDR methodologies like ERW through its CDR Purchase Pilot Prize through which it aims to purchase carbon credits generated through CDR pathways like ERW (DOE, 2024).

Legally, ERW projects must comply with existing environmental regulations such as the Clean Water Act and Clean Air Act, but there are no specific laws directly governing ERW at the federal or state level. Use of land for ERW, especially federally owned land, requires appropriate government approval, with agencies like the Bureau of Land Management (BLM) overseeing permits (Webb, 2020). ERW also offers agronomic co-benefits, improving soil pH and nutrient availability, which supports its adoption in agricultural policy frameworks.

In summary, U.S. policy encourages research and pilot projects on ERW as an innovative carbon removal and soil health practice, providing a positive government framework to potentially scale this technology while adhering to current environmental regulations. But no separate public policy for ERW exists yet.

2.2.6. UK:

The United Kingdom pursues Enhanced Rock Weathering (ERW) primarily through research, trials, and policy exploration aimed at greenhouse gas removal to support its Net Zero 2050 goal (Forrest and Wentworth, 2024). ERW is classified as an engineered greenhouse gas removal (GGR) technology and falls under the land use, land-use change, and forestry (LULUCF) sector in emissions reporting. Government-funded UK Research and Innovation (UKRI) trials actively investigate ERW's potential for carbon removal, soil fertility improvements, and crop yield benefits. It aims to incorporate CDR (including ERW) into the Emissions Trading Scheme by 2028 (Beerling et al., 2025).

UK policy recognizes ERW as potentially contributing significantly to CO_2 removal. However, policy also notes challenges such as scaling rock dust production, logistics of rock transport, environmental and social impacts, and the need for standardized measurement and verification systems. The UK's regional rock resources, mainly in

Scotland and northern England, and climate suitability are factored into planning for ERW deployment.

While ERW is not yet a quantified target in carbon budgets, it is included in the government's GGR portfolio in research and commercial pilot phases, with efforts to optimize quarry operations and reduce emissions associated with the supply chain (Forest & Wentworth, 2024). Overall, UK government policy supports advancing ERW through a cautious, evidence-based approach balancing carbon removal potential and environmental considerations. In case of the UK also, no current ERW specific policy exists.

2.2.7. Canada:

Canada's policy on enhanced rock weathering (ERW) is in a stage of developing clear regulatory frameworks to support carbon removal adoption while addressing environmental and health risks. Federal and provincial policies emphasize a high-rigor standard for carbon removal projects to build confidence for carbon credit buyers and investors. Policy priorities include dedicated ERW research and development funding, financial support for scaling and adoption, and robust environmental health and safety assessments to mitigate risks like heavy metal accumulation and dust inhalation during mineral spreading (Government of Canada, 2023).

Regulations increasingly focus on site-specific environmental risk assessments and monitoring plans that must accompany ERW projects applying to government programs. Canada's provinces hold jurisdiction over subsurface resources and carbon storage regulations, impacting ERW deployment on lands. The policy environment seeks to integrate ERW into carbon management strategies while aligning with existing regulatory frameworks for pollution and land use (Levy et al., 2024). The government also plans to buy 10 million CAD (Canadian dollars) worth of credit through CDR methods such as ERW. Thus, Canada's approach balances encouraging innovation in ERW as a carbon removal solution with the need for structured oversight to ensure safety and environmental protection.

2.2.8. EU:

The European Union's current policy landscape on enhanced rock weathering (ERW) is focused on evaluating ERW as a promising carbon removal technology under the broader Carbon Removal and Carbon Farming (CRCF) regulation. The European Commission is actively assessing how to include ERW within an EU-wide voluntary framework for certifying carbon removals to facilitate investment and market activity. ERW is recognized for its potential to significantly contribute to the EU's ambitious greenhouse gas reduction and carbon removal targets, but is not yet explicitly included within the certification framework (Beerling et al. 2025; CRCF, 2024). It is also supporting the development of robust MRV technologies for CDR through the C-SINK program (C-SINK) which aims to develop a standard and transparent carbon dioxide removal market.

Key policy efforts involve supporting extensive scientific research and demonstration projects to better understand ERW's carbon sequestration capabilities, environmental co-benefits such as soil pH improvement, and logistical challenges related to rock sourcing and transportation. The EU also acknowledges resource asymmetry across member states, which may affect deployment patterns and require coordination for efficient material use. Workshops and consultations are being conducted to develop certification methodologies aligned with high-integrity carbon removal standards, ensuring ERW deployments meet environmental and social safeguards. Currently, only Germany among the EU countries have regulatory boundaries regarding the amount of toxic elements in soil (Levy et al., 2024). Germany is also providing funding for CDR pathways such as ERW to satisfy its 2045 net zero targets through the CDRterra program (Beerling et al., 2025).

Overall, the EU promotes a cautious, evidence-based approach toward integrating ERW into its carbon removal portfolio, with plans to scale research, demonstration, and regulatory frameworks to unlock ERW's potential while balancing ecological and economic factors (CRCF, 2024).

Dimension	**Global South (Brazil, China, India)**	**Global North (United States, United Kingdom, Canada, European Union)**
Role of LULUCF	Central pillar of climate mitigation strategies; long-established forestry and land-use governance systems	Fully institutionalized within emissions accounting and carbon farming frameworks

Dimension	**Global South (Brazil, China, India)**	**Global North (United States, United Kingdom, Canada, European Union)**
Regulatory Strength (LULUCF)	High regulatory maturity; strong forest restoration and land governance systems	High regulatory maturity; embedded in national and supranational climate law
ERW-Specific Policy	No dedicated ERW policies; mostly absent from formal regulation and carbon crediting mechanisms	No standalone ERW laws, but active integration into research portfolios, certification design, and procurement planning
CDR Policy Ecosystem	Fragmented; limited dedicated CDR frameworks; policy focus on conventional CCS	Structured development of regulatory frameworks; certification methodologies under design
Focus of CCS Activities	Primarily geological storage and Enhanced Oil Recovery (EOR); aimed at reducing fossil fuel emissions	Greater orientation toward atmospheric carbon removal and net-negative strategies
Innovation Level (LULUCF)	High; established markets and restoration programs (though integrity concerns exist in some carbon markets)	High; integrated with carbon farming and greenhouse gas removal (GGR) programs
Innovation Level (Engineered CDR incl. ERW)	Generally low; limited demonstration projects; ERW largely confined to research (China shows higher patent activity)	Moderate to high; publicly funded R&D, pilot trials, early-stage commercialization pathways

Dimension	Global South (Brazil, China, India)	Global North (United States, United Kingdom, Canada, European Union)
Demonstration Projects (ERW/BECCS/DACCS)	Few large-scale operational projects; mostly research-stage or fossil-linked CCS pilots	Multiple pilot and field trials underway; inclusion in national carbon removal portfolios
Carbon Market Integration	Emerging systems (e.g., India ETS); ERW not typically recognized in crediting methodologies	Active development of voluntary certification systems and high-integrity carbon removal standards
Institutional Capacity for Scaling ERW	Limited policy scaffolding; discussion largely within expert and academic circles	Early-stage but coordinated market-building (MRV systems, environmental safeguards, procurement strategies)
Strategic Framing of CDR	Development-focused; emphasizes carbon space equity and fossil emission mitigation	Net-zero driven; views ERW as part of engineered greenhouse gas removal portfolios
Overall Positioning of ERW	High theoretical potential but low policy prioritization	Recognized as promising; progressing cautiously through research, pilots, and regulatory design

Table 4: Comparison of Global North and Global South on ERW & LULUCF-based CDR

2.3 Best Practices suggested in Literature

The effective use of ERW is controlled by a number of factors, including, rock type, soil quality and climate, among others (Fig. 2.7). Here we summarize some of the best practices as outlined in the ERW literature.

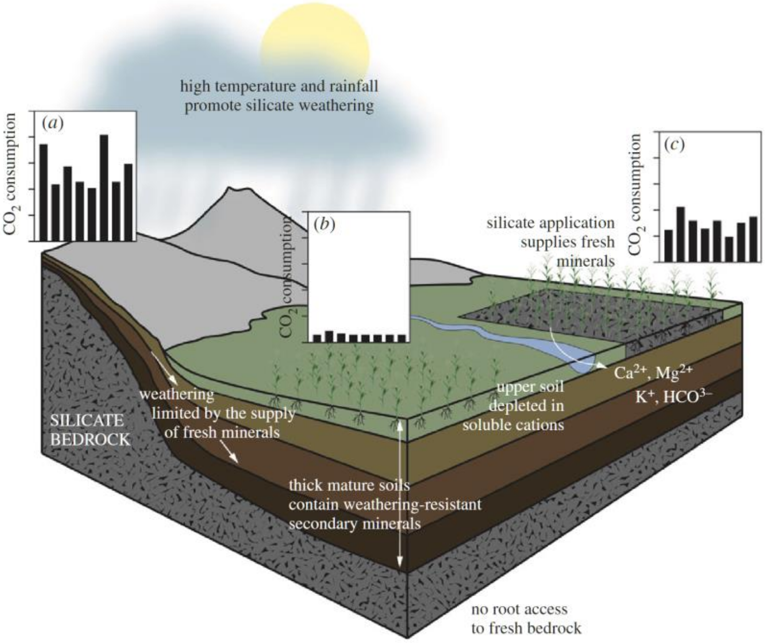


Fig. 2.7: Schematic illustration showing CO_2 removal through ERW in tropical climates. Also shown are the relative CO_2 consumption of eight hypothetical rivers draining (a) highlands with limited vegetation and thin/absent soil profiles (b) low-lying lands consisting of thick, mature weathering-resistant soils (c) lowlands with grounded basalt as ERW feedstock (reproduced from Edwards et al. 2017)

2.3.1. ERW Feedstock

Silicate minerals found naturally in igneous rocks are mostly used for ERW. Ultramafic rocks (with >90% mafic [Mg, Fe] minerals) like peridotite and minerals (like olivine) are often considered most suitable due to their low content of silica and high proportion of MgO and FeO. Similarly, rocks with high content of wollastonite and nepheline are preferred, due to the fast dissolution rates of these minerals (Fig. 2.8). Rocks that show high reactivity, containing minerals with fast dissolution rates are generally preferred (Manning, 2025; Vandeginste et al., 2024). Basaltic rocks containing the minerals plagioclase, pyroxene and olivine, are currently considered one of the most suitable rock types for ERW due to their high Ca, Mg and Fe content and widespread availability (Manning, 2025;

Swoboda et al., 2022). But there is considerable variation in the weathering rates of basalt depending on their mineralogy. Most initial studies overlooked this variation in weathering rates due to mineralogy, but recent studies suggest; that focusing on the most reactive basalts is probably the best way forward (Dupla et al., 2025). Factors such as base cation content, mineralogy, dissolution rates, trace element concentration, life cycle assessments, availability and cost-effectiveness are to be considered during the selection of suitable rock types (Abdalqadir et al., 2024; Dupla et al., 2025; Manning, 2022).

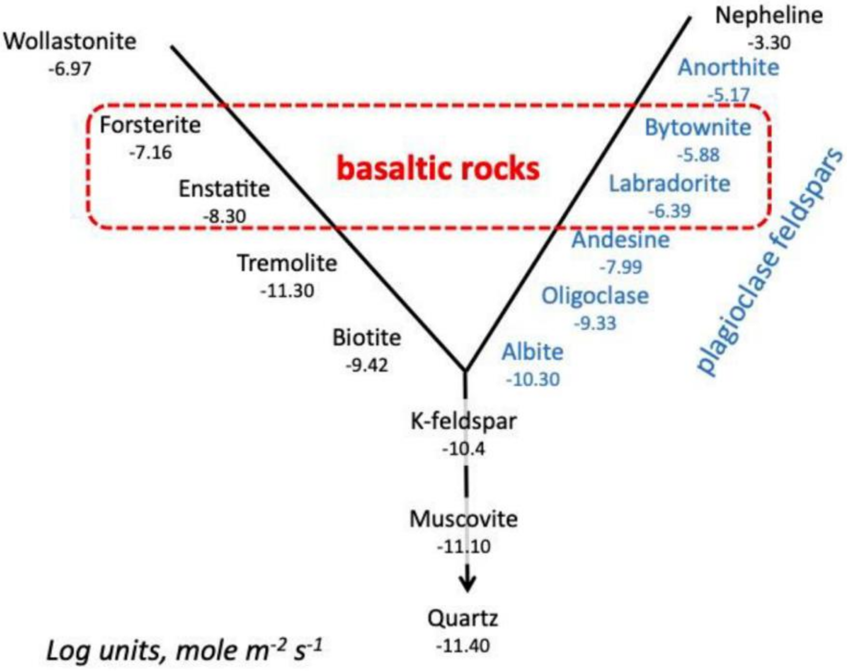


Fig. 2.8: Rate of dissolution of some common minerals used in ERW (reproduced from Manning, 2025)

In addition to rocks, alkaline materials produced during the manufacturing of steel, aluminium, cement, lime, nickel, etc. can also be used as feedstock materials for ERW. By-products from these industries such as steel slag, red mud, cement kiln dust, etc. contain silicate and hydroxide minerals which when dissolved in water can react with atmospheric CO_2 to produce bicarbonate ions (Renforth, 2019). The potential of such alkaline materials for carbon sequestration has been demonstrated in high temperature and high CO_2 pressure reactor experiments (Huijgen et al., 2005; Huntzinger et al., 2009). Since, these alkaline by-products are formed from high emission industries, the prospect of using them for CDR seems only natural to balance some of those emissions.

A prominent factor in choosing the type of ERW feedstocks is the consideration of accumulation of potentially toxic elements (PTE's) in the soil above levels that affect food production and safety (Hartmann et al., 2013; Renforth et al., 2012). Also, there is an additional risk of these PTE's migrating downward into the groundwater (Haque et al., 2020; Khalidy et al., 2023). This potential harm to the environment has been reported for olivine (Amann et al., 2020; Te Pas et al., 2023). For this reason, ultramafic rocks with high rates of dissolution which were initially considered best suited for ERW, are now a less preferred option– as they often contain high concentrations of nickel (Ni) and chromium (Cr) (Dupla et al., 2023). Although, mafic rocks like basalt contain considerably less amounts of PTE's like Ni and Cr, the concentrations are still high compared to those in soils (Kabata-Pendias and Pendias, 2001; Lar and Gusikit, 2015). Elements like Ni, Cr, copper (Cu) and zinc (Zn), among others are known for their low mobility and as such can accumulate in soils to high levels of concentrations. At high enough concentrations these elements may have toxic effects on crops, soil organisms and human health (Dupla et al., 2023; Sharma and Agrawal, 2005). However, it must be noted that some of these elements are also essential micro-nutrients useful to crops (Barral Silva et al., 2005). Therefore, it is essential to balance between the concentration of such elements such that they supply the essential amount, but do not become high enough in the soil that it poses risks to the environment and human health (Barral Silva et al., 2005; Haque et al., 2020).In addition to the above-mentioned elements, radiogenic elements which are often common in granitic rocks should also be avoided. The bioavailability of uranium (U) is strongly controlled by soil redox potential, pH, metal (hydr)oxides, etc. (Cui et al., 2023). Even thorium (Th) which is a weakly radioactive element can accumulate in soil due to its low mobility (Fesenko and Emlyutina, 2024), and both of these elements have harmful effects for human health, as is well known. Hence, rocks with these elements in high enough concentrations should be avoided. A list of PTE's along with reference to studies that highlight their toxicity is shown in Fig. 2.9. Compared to rocks, there is little research on the environmental effects from potentially toxic elements in alkaline industrial by-products (Renforth, 2019; Renforth and Henderson, 2017).

Asbestiform minerals – commonly referred to as asbestos in general, are a group of minerals that needs to be avoided due to their potential health hazards caused by their inhalation (Edwards et al., 2017; Ross et al., 2008; Taylor et al., 2016). These group consist of six minerals. These are chrysotile (belonging to the serpentine group) and five minerals from the amphibole group – actinolite, grunerite, anthophyllite, crocidolite and tremolite (Ross et al. 2008). It must be noted that some minerals from the amphibole and serpentine group that are classified as asbestos may not also occur with an asbestiform nature. For example, crocidolite is the asbestiform of riebeckite (amphibole group), but riebeckite can also occur in prismatic forms (Deer et al., 2013). In addition to asbestiform minerals, rocks with high concentration of sulphide minerals (like pyrite, sphalerite, galena, chalcopyrite, arsenopyrite, etc.) should also be avoided. Studies show that soil derived from sulphur mineralization leads to enrichment of toxic metal(loid) such as thallium (Tl), mercury (Hg) and arsenic (As) (Ma et al., 2020). Sulphides present in the rock can get oxidised into sulphates under sufficient moisture and aeration, and result in the formation of sulphuric acid resulting in a drastic fall of soil pH (Clemente et al., 2003; Förstner and Wittmann, 1981). This will generally have implications for both carbon sequestration and bioavailability of heavy metals (Clemente et al., 2003; Dupla et al., 2025). Additionally, under suitable soil pH conditions, adsorption of heavy metals like lead (Pb), cadmium (Cd), Hg and Zn may occur on sulphide minerals (Jean and Bancroft, 1986).

The availability and cost-effectiveness of ERW feedstock is also important to consider, since, they control the overall scalability of ERW both in terms of the carbon footprint and cost (Goll et al., 2021; Vandeginste et al., 2024).

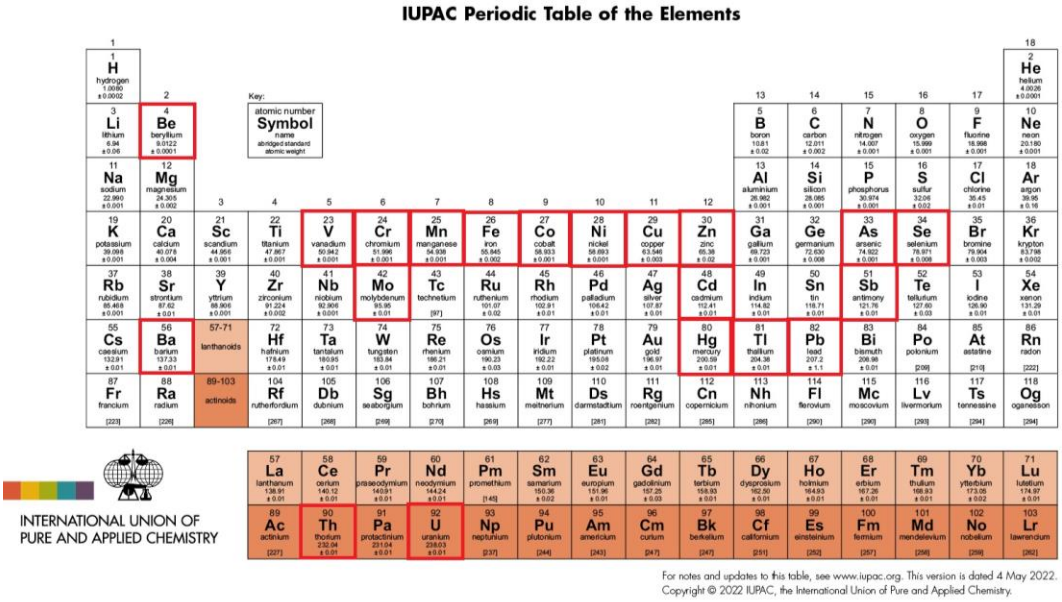


Fig. 2.9: Periodic table of elements showing the different potentially toxic elements (modified after IUPAC, 2022; Elguero and Alkorta, 2023; Bhoelan et al. 2014; Wnuk, 2023; Shija, 2026; Vidya et al. 2022; Cui et al. 2023; Fesenko and Emlyutina, 2024; Nieder and Benbi, 2024)

2.3.2. Soil properties

Soil properties like temperature, pH, moisture content, cation exchange capacity (CEC), etc. directly influence the rate of silicate weathering (Abdalqadir et al., 2024; Dupla et al., 2025; Zhang et al., 2025). Soil types like oxisols and ultisols prevalent in humid and sub-humid tropics are considered more suitable for ERW, compared to those from temperate zones due to their mineralogy (Sanchez, 2019; Van Straaten, 2006). In such soils, most of the primary silicate minerals have weathered to oxy-hydroxides and 1:1 clays, which reduces their CEC, pH and inherent nutrient supply (Swoboda et al. 2022). Another important factor to consider, but often ignored in the literature is the similarity between mineralogy of the rock and soil (Swoboda et al., 2022). Since, mineral dissolution is driven by ionic disequilibrium between the surface of the minerals and the soil solution, use of rock powders with similar mineralogy to the soil results in the system reaching equilibrium faster (White and Brantley, 2003). Any addition of further rock powder is unlikely to change this equilibrium conditions, and weathering rates will reduce significantly (Manning, 2018). These have been shown in studies also, that used the same rock type with same grain size on the same type of plants (Ramezanian et al., 2015, 2013). In case of similar soil and rock mineralogy, no increase in yield response was noted (Ramezanian et al. 2013), while for soil type with differing mineralogy significant increase was observed (Ramezanian et al. 2013).

The pH of soil affects the solubility and rate of dissolution of minerals, with more acidic soils favouring weathering processes (Bertagni and Porporato, 2022). However, extremely low pH can have a counter effect on ERW rates caused by the leaching of nutrients (Neina, 2019). Research suggests that soils with a higher cation exchange capacity (CEC) show higher potential for ERW and associated CDR. As the CEC of a soil increases, its ability to retain and facilitate nutrient cation exchange increases. This occurs due to the increase in surfaces with negative charge, which facilitates more cation absorption. Since more of the cation is captured within soil sites, it reduces the amount of cations that can get leached, and as a result nutrient cations are cycled more easily within the soil system (Vandeginste et al., 2024). But, this relationship between ERW and CEC is dependent on the composition of the soil and other environmental parameters (Calabrese et al., 2022). Due to its control on the availability of water, air exchange capacity, surface area available for reaction, particle contact size and leaching and transport processes, soil porosity also plays a major role in affecting ERW (Dalmora et al., 2016; Liu et al., 2017).

Similarly, soil moisture content has a strong effect on increasing the weathering rates as it makes more water available for the chemical reactions, along with enhancing dissolution, controlling temperature, affecting pH, facilitating microbial activity and helping element transport during weathering (Calabrese et al., 2022; Monger et al., 2015). An excess in soil moisture can also adversely affect ERW as it may lead to leaching and release of nutrients (Abdalqadir et al., 2024; Neina, 2019). Furthermore, studies show that soil texture, which is characterised by the relative abundance of clay, silt and sand, has direct control on the water retention capacity of soil and its porosity. This in turn affects the amount of surface area of the minerals available for reaction, thereby controlling ERW rates and rates of CO_2 sequestration (Abdalqadir et al., 2024). It is generally understood that application of ERW keeping in mind the local climatic and soil conditions will maximise the effect of ERW and the amount of CO_2 removed from the atmosphere.

2.3.3. Application rate

The application rate for ERW refers to the amount of rock dust applied per year per unit area. The amount of rock powder used depends on a number of factors, like rock type, CO_2

sequestration target and land area, and is still a matter of active research (Abdalqadir et al. 2024). Literature review shows that the amount of applied rock dust can vary between ~1 tonne per hectare (Bolland and Baker, 2000; Taylor et al., 2021) to as high as ~220 tonnes per hectare (Haque et al., 2019; Wood et al., 2023) across field, watershed, column and pot experiments. An increase in the application rate generally results in higher carbon sequestration. For example, in a study by Dietzen et al. (2018) increasing the amount of rock powder applied from 10 t/ha to 50 t/ha, led to an increase in CO_2 sequestration from 3.13 t/ha to 4.16 t/ha. But recent studies show, that this positive correlation is not always linear (Pogge von Strandmann et al., 2022). Very high application rates may also lead to nutrient imbalances and conflicting interaction between elements (Swoboda et al. 2022).

2.3.4. Monitoring, Reporting, Verification (MRV)

Monitoring, Reporting, and Verification (MRV) frameworks play a critical role in evaluating the effectiveness of ERW as a carbon dioxide removal technique. There currently does not exist a widely accepted MRV framework for measuring CDR rates related to ERW (Reershemius et al., 2023). Presently, MRV approaches include a large range of empirical measurement methodologies or modelling techniques that have been proposed to effectively estimate the amount of CDR from ERW. In the broadest sense, all MRV frameworks depend on measurement of one or more of the following: solid soil, water, gas or exchangeable phase measurements (Clarkson et al., 2024; Suhrhoff et al., 2025). Soil based measurements generally have the advantage of providing a time-integrated signature of weathering compared to water and gas-based calculations (Suhrhoff et al., 2024).

Since, ERW involves the transformation of atmospheric carbon dioxide into carbonates or bicarbonates through soil-based reactions, many authors have calculated the amount of inorganic carbon in soil to estimate the amount of CDR from ERW (Jariwala et al., 2022; Kelland et al., 2020). The amount of inorganic carbon can be broadly be divided into soil inorganic carbon (SIC) which are either insoluble, and dissolved inorganic carbon (DIC) (S. Yang et al., 2024). However, in some cases they can be sparingly soluble also (Sharififar et al., 2023). Since, DIC includes all inorganic carbon in a liquid – CO_2, carbonate, bicarbonate and carbonic acid- it is one of the best signatures for estimating the amount of bicarbonate formation from silicate weathering (Almaraz et al., 2022; Clarkson et al., 2024). The amount of DIC can be approximated from total alkalinity (TA) measurements, in case of neutral pH conditions prevalent in water. TA is used to measure the bicarbonate concentration in natural freshwaters, and is relatively simple to measure with no specialised equipment needed (Amann and Hartmann, 2022; Clarkson et al., 2024). Also, as the silica dissolution reactions takes place with the help of water, multiple studies have approached the problem of quantification of CDR through measuring the proportion of dissolved ions (mainly cations such as Ca^{2+} and Mg^{2+}) and carbonate alkalinity in soil porewaters or in the effluent waters (Amann et al., 2020; Kelland et al., 2020; Knapp et al., 2023; Renforth et al., 2015). Isotopic analysis of Sr, Li, Mg and C across soil, water and rocks has also been used to estimate weathering rates by many studies (Knapp et al., 2023; Pogge Von Strandmann et al., 2021, 2019). Innovative approaches have also been proposed to improve MRV precision and cost efficiency like the TiCAT method – which measures the concentration of cations in soil post application vis-à-vis immobile tracers such as Ti (Reershemius et al., 2023).

Modelling techniques to predict ERW weathering rates and associated CDR generally employ some form of reaction transport modelling (Deng et al., 2023; Kanzaki et al., 2022). There are instances of soil biogeochemical models being used for estimating changes in soil organic carbon (SOC) and for settling emission offsetting claims (Oldfield et al., 2022; Potash et al., 2025), although, studies have argued that these models are not advanced enough for calculating offsetting claims in their current state (Sutherland et al. 2024). Similarly, geochemical models have also been used for ERW (Kanzaki et al., 2024; Taylor et al., 2017). But geochemical modelling techniques currently employed tends to overestimate the weathering and CDR rates associated with ERW (Power et al., 2025). A major shortcoming of these reaction transport modelling-based approaches is that these are mostly one-dimensional modelling and hence, does not account for the changes in chemistry and movement of elements in the other two dimensions.

Recently, (Power et al., 2024) and (Grubert and Talati, 2024) have shown the advantages of developing advanced MRV protocols incorporating geochemical modelling and novel in-situ measurement methods. (Rieder et al., 2024) contribute by proposing soil electrical conductivity (EC) and volumetric water content as cost-effective proxies to monitor alkalinity and dissolved inorganic carbon linked to carbon sequestration, thus enabling scalable monitoring. Similarly, (Amann and Hartmann, 2022) advocate leveraging correlations between total alkalinity (TA) and EC, offering a simplified and less expensive MRV approach compared to traditional labour-intensive sampling, which could accelerate standardized ERW project monitoring. Current studies suggest the application of soil-based mass balance approach as a promising avenue for developing robust MRV frameworks (Clarkson et al., 2024; Reershemius et al., 2023; Suhrhoff et al., 2024).

(Almaraz et al., 2022) emphasize the foundational need to accurately measure soil organic and inorganic carbon pools, dissolved inorganic carbon in soil pore water, and greenhouse gas emissions. These metrics provide a comprehensive account of carbon sequestration rates, allowing robust verification of ERW's effectiveness. Such precision is essential because ERW's carbon capture efficacy varies across soil types, climates, and rock amendment applications, necessitating standardized MRV protocols that can flexibly address diverse contexts (Abdalqadir et al., 2024). Other studies like, (Santos et al., 2023) highlights the uncertainties involved in verification methods, such as soil water analysis and remote sensing. They underscore the challenge to develop scalable, feasible, and equitable verification practices that maintain accuracy across different deployment scales and geographies. Similarly, Vandeginste et al. (2024) stress the importance of integrating sound policies with scientific methodologies to build MRV frameworks capable of capturing the long-term durability and magnitude of CO_2 sequestration by ERW. Likewise, (Schenuit et al., 2023) and (Hagens et al., 2023) advocate for strong certification schemes and reliable MRV frameworks to ensure measured carbon sequestration aligns with actual removal, reflecting the ongoing research momentum to develop MRV technologies tailored specifically to ERW.

The MRV process itself is systematic and multi-staged (Fig. 2.10). It generally considers a baseline dataset containing empirical data across a range of parameters related to soil properties climatic factors and geochemical characteristics. These are then compared with data collected post application at regular intervals to measure the amount of atmospheric carbon dioxide removed and changes in soil properties. It begins in the "Pre-Implementation" phase, with careful site selection based on geological, climatic, and soil baseline carbon assessments. During "Implementation," precise documentation of rock application—rates, methods, timing—is essential. The "Monitoring" phase is central, involving soil and water analyses to detect changes in alkalinity, EC, and other carbon sequestration indicators, including greenhouse gas flux measures and remote sensing for large-scale impact assessments. Cost-effective proxies like EC measurement enhance feasibility for widespread monitoring. The "Reporting" phase synthesizes data into comprehensive assessments communicated to stakeholders, while "Verification" ensures third-party audit and validation of carbon sequestration claims, securing project integrity.

Finally, “Feedback and Adjustment” cycles allow continuous MRV improvement, culminating in “Certification and Recognition,” where projects earn marketable carbon credits, acknowledging their contributions to climate change mitigation (Abdalqadir et al. 2024).

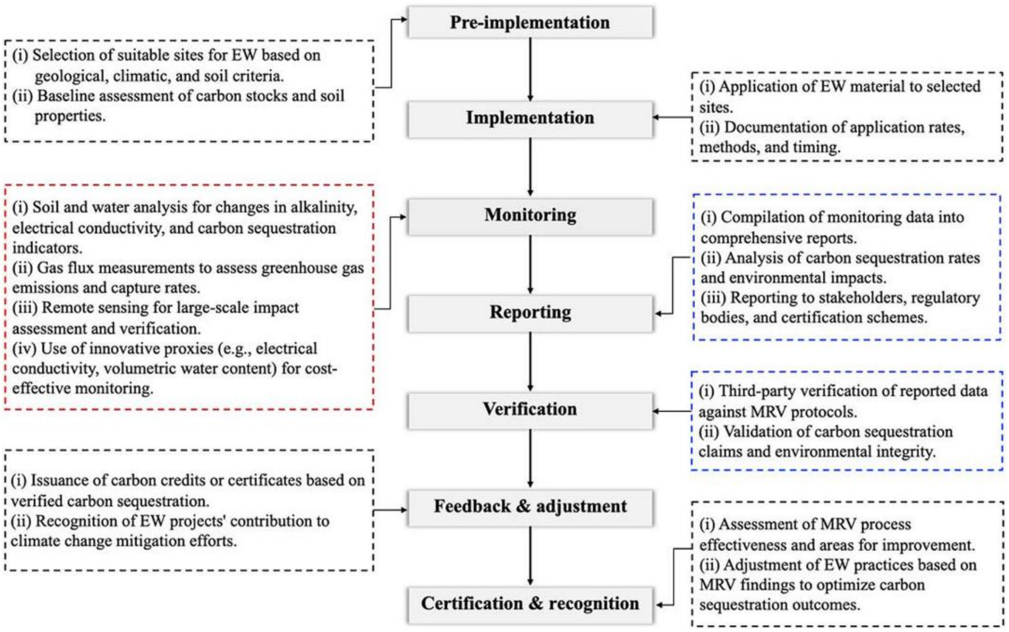


Fig. 2.10: Flowchart showing the different stages generally associated with the MRV process in ERW (reproduced from Abdalqadir et al. 2024)

2.4 Current Gaps

2.4.1. Literature

Estimating the amount of carbon dioxide removed during enhanced rock weathering is challenging due to the inherently complex and open nature of the system (Power et al., 2025). This challenge is exacerbated by the slow dissolution rates of the silicate minerals and variability in weathering across space and time. Moreover, determining the amount of CO_2 stored either in the form of a mineral or as a soluble phase presents additional challenges (Clarkson et al., 2024; Sandalow et al., 2021). One of the major limitations of current methods of measurement is that they use indirect measurements to determine the amount of CO_2 removed, instead of directly measuring the carbon (Clarkson et al., 2024).

Multiple factors like grain size, soil pH, temperature, etc., introduce uncertainties in determining CDR from ERW (Abdalqadir et al. 2024; Dupla et al. 2025). Constraints also occur in terms of verification methods (Santos et al. 2023). Studies like Calabrese et al. (2022) and Power et al. (2025) highlight the discrepancies between theoretical and model predictions with lab and field observations. Studies have also highlighted the difference between thermodynamic saturation of laboratory experiments versus field conditions. While most experimental determinations of weathering rates take place under far from thermodynamic saturation conditions, most soil solutions are actually close to thermodynamic saturation with respect to primary minerals (Dupla et al. 2025). These has led to what is referred to in the literature as 'field-lab discrepancy' in terms of weathering rates, with lab-based estimates being 1-4 orders of magnitude higher than those observed in the field (White and Brantley, 2003).

Another major issue with using the dissolution rates and other related data for actual ERW projects lies in the fact that these are performed under idealised laboratory conditions, compared to field conditions (White and Brantley, 2018). While parameters like pH, temperature, water flux, etc. remain constant under laboratory conditions; they fluctuate in real world field conditions, with possible interdependencies and attenuation effects (Swoboda et al. 2022). Additionally, many studies report incorrect rock names as they are mostly led by crop scientists, who are unaware of the rigorous methodology involved in rock naming (Swoboda et al., 2022). Also, quarry owners from which rock powders are sourced for such experiments or ERW projects often use terminologies that are aligned with construction markets. As a result, it is often difficult to reproduce results from such studies and even for evaluating the results from such weathering studies (Swoboda et al. 2022). Therefore, it is difficult to assess in many cases, the ability of different material to sequester carbon. Moreover, as rocks are composed of multiple minerals, it is important to consider bulk dissolution rates that consider the mineralogy of the rock, along with their textural relationships (Manning and Theodoro, 2020).

While evidence related to ERW can be gauged from long term forest trials ranging from several years to several decades (Long et al., 2015; Taylor et al., 2021), agronomic studies typically last from several months to two years (Swoboda et al. 2022). This is problematic since, compared to water soluble artificial fertilizers, the rock powders are slow releasing fertilizers (Swoboda et al. 2022). As such, short term studies fail to capture the changes to soil health. Due to their slow dissolution, effects from rock powders typically can take a year or more to show up (Aarnio et al., 2003). Therefore, more long-term studies are required to fully understand the effects of ERW (Manning, 2010; Winiwarter and Blum, 2008). Moreover, the limited long-term studies that are available are mostly from the Global North and Brazil. Currently, there is no peer reviewed long-term or short-term study from India regarding the agronomic effects of ERW in Indian conditions.

Some of the pitfalls that still need to be addressed to prevent overestimating CDR from ERW include initial fast dissolution of minerals and labile phases, weathering of accessory carbonates, not quantifying carbon but rather cations, among others (Power et al. 2025). Scientists have also warned that upscaling CDR rapidly can give rise to environmental, climate and social problems similar to those we are trying to mitigate. This has already been seen in the case of biofuels (Buck, 2016). Literature studies show that currently there is no method for measuring CDR from ERW which is universally accepted (Power et al. 2025). Higher CDR rates mean higher carbon credits for private companies. This may result in overestimation of CDR rates eventually undermining ERW credibility, similar to forest-based credits (Badgley et al. 2022; The Guardian, 2023). Therefore, more research is needed to correctly determine the quantification of CDR related to ERW.

To ensure ERW's role as a reliable CDR strategy, further research is urgently required to refine measurement techniques, develop robust verification frameworks, and establish standards that accurately capture carbon sequestration. Strengthening the scientific foundation for ERW will support informed policy decisions, safeguard climate integrity, and enhance the credibility of carbon market mechanisms, positioning ERW as a viable and accountable tool within India's climate mitigation portfolio.

2.4.2. Policy

Climate modellers have recently come under criticism for using CDR technologies as part of their climate assessment models (Hasegawa et al., 2021; Pedersen et al., 2021) due to two primary reasons. Firstly, researchers argue that CDR methodologies have sustainability trade-offs (for example, with bio-diversity and food security- (Anderson, 2015; Creutzig et al., 2021)). Secondly, researchers point to a moral problem with CDR, suggesting that large-scale deployment of CDR can result in hindrance of reducing emissions (McLaren et al., 2019; Morrow, 2014). To address these issues, modellers have either enlarged the CDR portfolio to include technologies like ERW, or attempted to reduce their dependence on CDR for integrated assessment modelling. More studies integrating such different modelling approaches with social sciences to create integrated assessment models for achieving climate goals are needed (Cherp et al., 2018; Pianta and Brutschin, 2022).

Review of the current practices in CDR (including ERW) governance and policymaking show major differences between countries in terms of the path taken and point to deficiencies in the regulatory framework to facilitate large scale deployment of CDR, including ERW as part of climate policy (Schenuit et al., 2025, 2021; Smith et al., 2023). Although, the use of CDR as one of the climate change mitigation pathways is generally more prevalent in the Global South (Schenuit et al., 2025), most studies on CDR governance and policymaking have been restricted to OECD countries (Bellamy et al., 2021; Fridahl et al., 2020). Although, research in CDR methodologies like Direct Air Capture and Carbon Storage (DACCS), Bioenergy with Carbon Capture and Storage (BECCS), Enhanced Rock Weathering (ERW), etc., are increasing; high level of uncertainty is still associated with modelling CDR deployment (Schenuit et al. 2025). There is also a lack in research on public perceptions of ERW. The limited studies are mostly dominated by survey studies with few qualitative and deliberative research (Cox et al., 2022). Strengthening understanding of governance frameworks, modelling uncertainties, and public perceptions will be critical for designing effective, scalable, and socially-inclusive ERW policies, ensuring that CDR strategies contribute reliably to national and global climate mitigation goals.

CHAPTER 3 – STAKEHOLDER ENGAGEMENT REPORT

3.1. Overview

Carbon Dioxide Removal (CDR) encompasses human-led activities aimed at extracting CO_2 from the atmosphere and securely storing it in geological formations, terrestrial ecosystems, or oceanic reservoirs. CDR can be categorised into two broad types—*conventional methods*, such as afforestation and reforestation, and *novel technologies*, including Enhanced Rock Weathering (ERW) and Direct Air Capture with Carbon Storage (DACCS) (Smith et al., 2023).

Recent scientific literature emphasizes the growing role of private organizations in advancing and governing CDR initiatives (Dörpmund, 2025). However, despite their central role, academic discussions integrating private-sector perspectives into formal policy design remain limited and fragmented (P. Yang et al., 2024). As the world approaches COP30, attention increasingly focuses on the evolution of carbon governance, which has evolved significantly since the Kyoto Protocol (1997) introduced structured market tools for mitigation.

3.2. Global Carbon Market and CDR Market

The Kyoto Protocol (1997) laid the foundation for the Global Carbon Market (GCM) by embedding flexible mechanisms aimed at achieving climate targets cost-effectively. These instruments allowed nations and organizations to mitigate emissions through a combination of emission avoidance, reduction, and removal (Johnstone et al., 2025).

Despite over two decades of deliberation in international climate forums, the GCM remains largely unimplemented at a unified global scale Instead, a series of voluntary and regional markets operate independently, occasionally interconnected where arbitrage opportunities exist (Asadnabizadeh and Moe, 2024).

Within this fragmented landscape, CDR has emerged as a critical but nascent segment of the carbon market. While national decarbonization plans generally underrepresent CDR, private initiatives —particularly within the Voluntary Carbon Market (VCM)—have driven early development. Registries such as Verra, Gold Standard, Puro.earth, and Isometric are at the forefront of establishing methodologies and issuing credits for novel pathways like ERW and DACCS.

3.3. Carbon Credits

A *carbon credit* denotes one tonne of carbon dioxide equivalent (CO_2e) avoided, reduced, or removed (Fig. 3.1) in accordance with approved methodologies and validation processes (Johnstone et al., 2025). These credits are tradable assets within carbon markets and represent quantifiable units of climate mitigation.

In the current landscape, CDR-related credits are predominantly issued and traded in voluntary markets, given the absence of robust integration of CDR in national compliance regimes (Fig. 3.2). The voluntary carbon market, valued at approximately $2 billion in 2021, is projected to grow substantially, with estimates suggesting it may reach $10–40 billion by 2030 (Delacote et al., 2024).

Private companies engage with carbon credits for multiple purposes:

- To offset residual emissions in pursuit of net-zero goals.
- As part of corporate social responsibility (CSR) and sustainability initiatives.
- To test and pilot compliance models in anticipation of future regulatory markets.

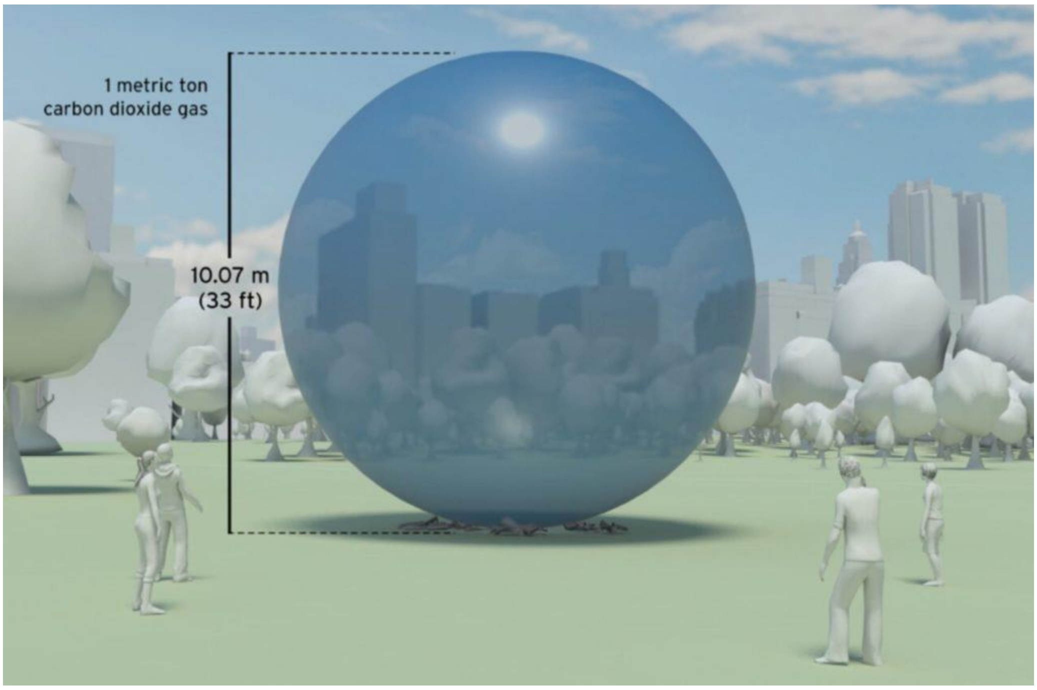


Fig. 3.1: 1 carbon credit equivalent of CO_2 (Image by Carbon Visuals, “The Case For Carbon Capture & Storage” – 2015)

Overall, carbon credits serve as the cornerstone of emerging CDR markets, providing financial mechanisms that incentivize both emission reduction and active carbon removal innovations.

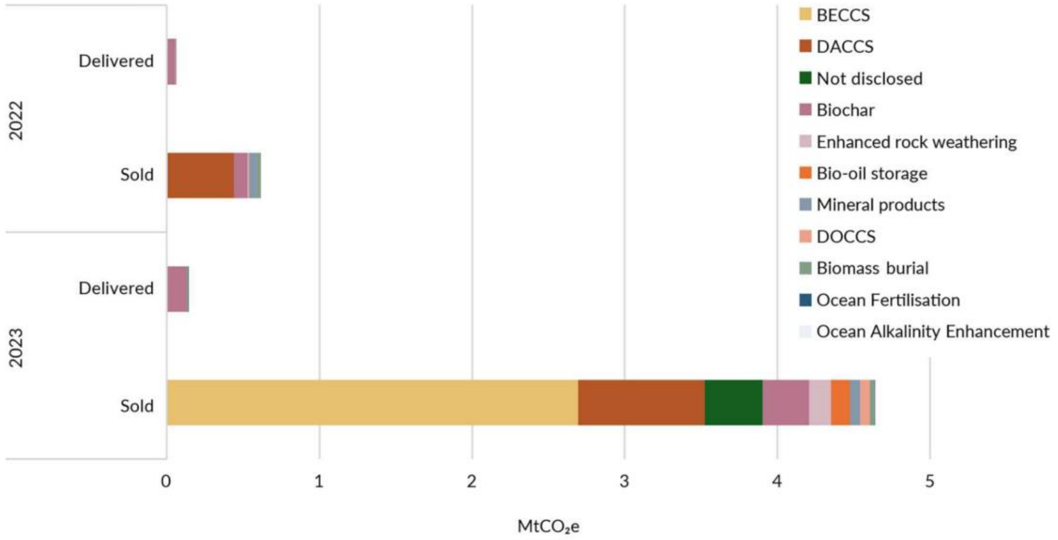


Fig. 3.2: The volume of CDR sold or delivered in the voluntary carbon market (VCM) for the years 2022 and 2023. [BECCS=bioenergy with carbon capture and storage; DACCS=direct air carbon capture and storage; DOCCS=direct ocean carbon capture and storage] (reproduced from Johnstone et al. 2025).

3.4. ERW in India

Several companies are actively involved in enhanced rock weathering (ERW) projects across India, including Varaha, Alt Carbon, Mati Carbon, Everest Carbon and Carbon Clean Solutions, with projects focused on carbon removal and improving soil health, particularly in agricultural areas. Their details are given below (Table 5):

Sr. No.	Name of the organization	Project's location	Current Status
1	Varaha	Khargone, Madhya Pradesh	Active
2	Alt Carbon	Darjeeling, West Bengal	Active
3	Mati Carbon	Raipur, Chhattisgarh	Active

4	Everest Carbon	Neemuch, Madhya Pradesh	Presently, not actively pursuing ERW in India
5	Carbon Clean Solutions	India	Shifted approach away from ERW

Table 5: List of companies that worked/working on ERW in India. Details given following information in their respective websites.

In addition to the above companies, multiple organisations are active in India acting as key enablers for ERW and CDR in general. For example, the National Center of Excellence in CCUS (IIT Bombay) and Council on Energy, Environment and Water (CEEW) are prominent among the institutional and research enablers active in India. [remove] India Accelerator and the Indo-Danish Green Strategic Partnership are some of the platforms that support innovation and start-ups in the CDR space. The Bureau of Energy Efficiency (Government of India) is actively working towards creating a viable carbon market in India. The Carbon Removal India Alliance (CRIA), a multi-stakeholder alliance focused on catalysing a scalable and high-integrity carbon removal sector in India is also present in this sector.

3.5 Stakeholder Consensus on ERW feasibility & scalability

- Soil saturation and carbon sequestration longevity

Topic/Parameter	**Broad Consensus (Most Experts)**	**Diverging Opinions (Other Expert Views)**	**Literature Support**
Soil Saturation and Carbon Sequestration Longevity	**Soil Saturation:** – Most experts agree that soil saturation occurs gradually and is influenced by application rates and monitoring over time. – Several trials reported ERW application rates range	**Soil Saturation:** – One expert raised scepticism regarding saturation timelines, stating that soil rejuvenation potential is uncertain, and long-	The literature concurs with the majority view (Beerling et al. 2025; Manning, 2025) The diverging views among

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	broadly from 2–200 tonnes/ha, while a conservative application (around 30-40 tonnes/ha) is recommended to avoid negative impacts such as soil degradation and reduced plant growth due to high alkalinity and reactivity. – Applications are generally gradual, with initial application followed by reapplication after ~2–3 years, though observations suggest it could extend to ~5 years or vary depending on soil conditions and biological mixing. Long-term evidence is limited, and practical implementation may be constrained by costs of repeated farm visits and regional differences in soil bioturbation and incorporation processes. – Field data (e.g., from basalt applied over 3 years) suggest continued weathering, with no clear	term effects remain unverified. – Emphasized that more studies are needed to confirm whether ERW can continue indefinitely without negative consequences. – Warns that commercial interests may lead to underreporting saturation risks, and urges caution due to possible impacts on food security. **Longevity of CO_2 Sequestration:** – No major divergence on geological durability, but concern	the stakeholders has also been reported in literature (Delacote et al. 2024)

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	evidence of soil saturation yet. **Longevity of CO_2 Sequestration:** – There is strong consensus that ERW offers very long-term carbon sequestration i.e.,>10,000 years geologically, with 100-year permanence suitable for carbon registries. – Experts agree that there are no significant back-emissions within that timeframe, making ERW attractive for durable CO_2 removal. – Depending on the CDR target of a specific project, it would decide if the carbon is to be precipitated as a carbonate within soil or to be kept as a bicarbonate in solution. **Downstream Environmental Effects**	is indirectly implied through calls for long-term monitoring and transparency regarding permanence claims. – One of the stakeholders also pointed out, that while ERW is in its initial stages of scientific knowledge and can be beneficial for farmers, it is not a viable and scalable solution for climate change.	

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	(Groundwater and Surface Water): – Detectability of downstream effects: ERW signals from single applications are very small, making direct detection of downstream impacts at small scales difficult; long-term modelling may be needed to better understand potential effects. **Observed environmental impacts:** – No significant negative downstream effects have been reported so far; the only noted change is minor variations in aquifer chemistry, considered part of natural background processes. **Potential environmental concern:** – The main aspect requiring management is the movement of particulate matter through surface		

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	water, which could pose a concern if not properly controlled.		

- Barriers to scaling Enhanced Rock Weathering (ERW) nationally or regionally

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
Barriers to scaling ERW	**Infrastructure, finance, and farmer engagement are key barriers.** – Feedstock access (e.g., quarries/mines) and land access are common logistical bottlenecks. Legal complexities, permits, and lack of alignment between landholders and quarry owners delay projects. – Financial challenges, especially upfront capital requirements and lack of investor confidence—significantly slow project initiation.	**More technically nuanced or region-specific concerns were raised by some experts.** – One expert emphasized transportation and local sourcing issues, pointing out that long-distance hauling of rocks increases emissions and costs, thus hurting ERW's Life Cycle Assessment (LCA). – Some regions have inadequate basalt quality (e.g., altered basalt in Orissa) or incompatible soil chemistry (e.g.,	The academic literature broadly concurs with the stakeholder views (Dörpmund, 2025)

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	– Farmer participation is unreliable, with high dropout rates, affecting project continuity, but in case of positive results in terms of crop yields, more farmers do become interested with demand for rock powder from farmers outstripping supply. – Monitoring challenges (e.g., equipment theft, poor field reliability) undermine MRV systems. – Experts also broadly agree that lack of awareness, weak policy, and limited buyer demand for high-cost durable carbon credits further constrain scaling. – Another key barrier to large scale deployment was the availability of enough rock for scaling ERW without opening new quarries/mines. Opening of new quarries/mines for ERW feedstock sourcing negates much of the environmental benefits and	arsenic contamination, unsuitable pH). – Scaling ERW will likely require use of multiple rock types, rather than reliance on a single mineral source. – Crop type and water usage also affect ERW effectiveness—e.g., slow weathering in crops like sugarcane. – Another expert warned that high ERW credit costs ($200–$500/ton) and overreliance on a few big buyers make the market fragile and unscalable in its current form. – There are calls for more social science research to ensure long-term farmer engagement and locally adapted strategies.	

Topic/Parameter	**Broad Consensus (Most Experts)**	**Diverging Opinions (Other Expert Views)**	**Literature Support**
	does not make it a sustainable practice.		

- Monitoring, Reporting and Verification (MRV)

Topic/Parameter	**Broad Consensus (Most Experts)**	**Diverging Opinions (Other Expert Views)**	**Literature Support**
MRV	**Core Purpose and Structure of MRV** – MRV is essential for establishing credibility, transparency, and market trust in ERW carbon credits. –MRV integrates local QA/QC tests (XRD, SEM-EDS, ICP-MS) and field comparison of treated vs. control plots to demonstrate carbon capture validity. – Standard QA/QC tools like XRD, SEM-EDS, and ICP-MS are accepted for validating mineral and chemical characteristics.	**Alternative or Emerging MRV Systems** – A new resin-based in situ bicarbonate capture method has been introduced to replace traditional lab-based analyses, providing real-time, field-level monitoring for measuring CO_2 sequestration directly from soil porewater. – This technique reduces reliance on ICP-MS or IC systems and lowers MRV costs while maintaining accuracy.	The literature supports the broad consensus on the importance of MRV (Abdalqadir et al. 2024). Though concerns regarding the various aspects of MRV still exist (Bijma et al., 2026); (Power et al. 2025)

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	– Consensus on using existing soil health and agronomic indicators (pH, nutrient availability, organic matter, alkalinity) rather than developing entirely new metrics. – Emphasis on field-based measurements of bicarbonate flux, soil alkalinity, and mineral weathering rates to quantify CO_2 drawdown. **Protocols & Registry Alignment** – Most experts align ERW verification with Voluntary Carbon Market (VCM) standards, notably Puro.Earth and Isometric Registry play a central role in project validation, issuance of credits, and maintaining quality standards. – EU's CRCF and Article 6.4 of the Paris Agreement are cited as policy references for harmonizing	– Continuous soil data collection improves temporal resolution and enables dynamic tracking of weathering reactions. – Some advocate moving toward universal verification frameworks (e.g., Carbon Plan, Cascade Climate) instead of site-specific or registry-specific methods. **Alternative Methodological Development** – Some experts highlight emerging registries (e.g., Rainbow, Carbon Standards International, One-Shot Earth) and ongoing efforts to refine methodologies for field-scale adaptability. – Certain practitioners prioritize local documentation and transparency to build	

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	global carbon crediting standards. – MRV frameworks emphasize quantifying net CO_2 removal = drawdown − system emissions. – Auditors or VVBs (e.g., 350 Solutions) conduct independent field audits and desk reviews to confirm compliance. – MRV directly determines project eligibility for carbon credit certification and payment. **Key Parameters and Indicators** – Solid phase measurements (like the Ti-CAT method) are preferable as they provide a time-integrated result. – Most current methods do not directly measure final carbon sequestration fate. – Aqueous measurements provide data from snapshot of time and can	trust before formal registry inclusion. – Some practitioners emphasize the need for isotopic fingerprinting ($\delta^{13}C$) to distinguish between atmospheric and biological CO_2 sources for higher scientific precision. **Local Adaptation of Standards** – Some stakeholders advocate for region-specific MRV customization, especially for tropical soils and crop systems where ERW reactions differ from global-north conditions. – Local registries or government-backed frameworks could help reduce dependence on expensive global VCM verification routes. **Cost Reduction Strategies**	

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	measure parameters such as bicarbonate and dissolved inorganic carbon in the water system. – Consensus that MRV should monitor bicarbonate flux, soil pH, cation concentration, carbonates in soil and water, and energy or fuel used for transport and spreading. It should include both solid phase and aqueous measurements. – Digital MRV systems must be used to capture geotags, timestamps, and photos across sourcing to application for verifiable ERW records. – Plot designs should include intensive treatment (4–5 soil samples/ha, at least), extrapolative deployment (1 sample/5 ha), and control plots (no amendment) for robust monitoring.	– Field innovators suggest MRV should rely more on soil agronomic parameters (pH, nutrient status, alkalinity) rather than high-cost instrumentation as MRV comprise the highest cost component of any ERW project. – The resin-based bicarbonate measurement and use of crusher tailings from local quarries are seen as ways to cut MRV and LCA emissions simultaneously. – Some propose MRV costs should ideally be 5–10% of total project expenditure, not the current high share. **Scientific Enhancements** – Advanced methods, including isotopic tracing, cation–bicarbonate balance	

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	– Carbon Plan's Verification Framework is recognized as a reference for scientifically credible MRV parameterization. – MRV distinguishes itself from LCA — it focuses on measured, real-world performance, not modeled projections. – Soil and water sampling, mineral application records, and transport data are key datasets for validation. **Verification and Validation Standards** – MRV processes are linked to Voluntary Carbon Market (VCM) registries such as Puro.Earth and Isometric, which define methodologies and reporting standards. – Registries and auditors collaboratively review project documentation,	calibration, and adaptive soil pH management (5.5–6.5 range), are recommended to enhance accuracy. – Some highlight that high cation exchange capacity (CEC) soils can trap ions and distort bicarbonate accounting, requiring site-specific calibration. **Alternative Governance Models** – Some experts suggest public or hybrid governance models (involving governments, academic labs, and local cooperatives) to complement registry-based systems, especially for developing countries to lower entry barriers.	

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	data, and results before issuing credits. – Verification frequency varies — monthly, quarterly, or annually — depending on project scale and registry norms. – Independent auditors are required to minimize bias and ensure due diligence. **Cost and Feasibility Considerations** – MRV is acknowledged as the largest cost driver in ERW projects, often consuming 70–80% of total expenses in small-scale initiatives. – Major cost components include auditor and registry fees, lab testing, sampling logistics, and DMRV platforms. – Larger projects achieve better cost efficiency through economies of scale.		

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	– There is agreement that MRV credibility justifies its cost, as “MRV is the product” — without it, credits hold no market value. **Scientific Challenges and Uncertainties** – Measuring CO_2 removal in open systems like ERW remains complex due to environmental variability and carbonate transport in ecosystems. – Uncertainties are mitigated by multi-point sampling, computational modeling, and comparative baselines (treated vs. control plots). – Continuous improvement and methodological refinement are essential for global MRV harmonization. **Institutional Roles and Market Linkages**		

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	– Multiple actors participate in MRV: start-ups, farmers, mineral suppliers, registries, VVBs, investors, and buyers. – Registries create the methodologies; VVBs ensure independent validation; project developers maintain operational transparency. – Trust in MRV directly drives carbon credit pricing and buyer confidence in the VCM.		

3.6 Stakeholder Consensus on Socio-Economic Impacts

- Impacts on Crop Yield and Soil Health

Topic/Parameter	Broad Consensus (Common Views)	Differing Opinions / Unique Perspectives	Literature support
Crop Yield and Soil Health	**ERW can improve crop yields and soil health:** – Most stakeholders reported that applying	**Magnitude of yield increase is uncertain:** – Some stakeholders caution that existing	The academic literature broadly concurs with

Topic/Parameter	Broad Consensus (Common Views)	Differing Opinions / Unique Perspectives	Literature support
	silicate rocks (e.g., basalt) can enhance soil fertility and crop productivity.	evidence is not yet rigorous or sufficiently comparable across studies to confidently quantify yield improvements.	the stakeholder views (Swoboda et al. 2022).
	Improved soil chemistry is a key mechanism: – Weathering of silicate minerals releases beneficial cations (e.g., calcium and magnesium), raises soil pH, and enhances nutrient availability—factors that support plant growth and soil fertility.	**Yield gains may be modest in well-managed soils:** – In soils already receiving fertilizers or proper management, the yield increase from ERW may be relatively small (sometimes only a few percent).	
	Positive yield responses have been observed in multiple field contexts: – Several case studies and trials report substantial increases in crop yield following rock application.	**Greater benefits mainly in degraded or poorly managed soils:** – Some emphasize that the most noticeable yield improvements occur in nutrient-depleted or degraded soils rather than in fertile, well-managed agricultural systems.	

Topic/Parameter	**Broad Consensus (Common Views)**	**Differing Opinions / Unique Perspectives**	**Literature support**
	Soil properties strongly influence ERW effectiveness: – Soil type, soil quality, and pH conditions play a major role in determining both weathering efficiency and crop yield responses.	**Specific soil chemistry constraints:** – Some highlight additional factors such as sulfur content, strong acid anions, or very low pH conditions that may limit ERW effectiveness or increase reversal risks.	
	Acidic or nutrient-depleted soils may experience strong co-benefits: – Several stakeholders note that ERW can help buffer soil acidity and replenish nutrients, leading to improved crop productivity.	**Soil texture can influence weathering dynamics:** – In loamy soils, released cations may bind to cation-exchange sites, potentially slowing carbon removal processes even though soil fertility benefits remain.	
	ERW can contribute to long-term soil health improvements: – Beyond yield gains, stakeholders emphasize benefits such as improved soil structure, enhanced nutrient	**Yield increases may plateau over time:** – Some observations suggest that yields may increase initially due to additional nutrients but may not continue rising indefinitely once nutrient balance stabilizes.	

Topic/Parameter	Broad Consensus (Common Views)	Differing Opinions / Unique Perspectives	Literature support
	cycling, and sustained productivity over time.		
	Agricultural co-benefits are important for farmer adoption: – Farmers are primarily motivated by improved crop yields, soil quality, and economic returns rather than carbon removal alone.	**Feedstock choice can target specific agronomic goals:** – Different rock types may be selected depending on the objective—for example, potassium-rich rocks for nutrient enrichment versus basalt for broader soil health benefits.	
	Scientific trials and monitoring are necessary: – Stakeholders emphasize the importance of controlled plots, field trials, and long-term monitoring to verify yield improvements and soil health outcomes.	**Policy and agricultural program integration:** – Some perspectives highlight aligning ERW with existing agricultural policies aimed at reducing fertilizer or liming use, while acknowledging potential economic trade-offs (e.g., impacts on limestone industries).	

- Environmental Risks and Safety

Topic/Parameter	**Broad Consensus (Majority View)**	**Differing Opinions / Unique Perspectives**	**Literature support**
Environmental Risks and Safety	**Key Environmental Risks Identified** – Dust generation during grinding, transport, and field spreading is a major health and air-quality concern for workers and nearby communities. – Heavy metal contamination (e.g., lead, arsenic, nickel) in mineral feedstock poses a critical risk to soil, crops, water, and food safety. – Soil integrity can be damaged by over-application of minerals, leading to long-term productivity loss and structural degradation. – Land use change risks arise when quarrying or ERW-related land conversion disturbs	**Field Experience and Risk Minimization through Site Screening** – Some practitioners report no significant environmental issues in their ERW field projects so far, attributing this to strict pre-deployment screening and site selection. – Baseline soil testing for pH and basalt quality ensures unsuitable sites or poor feedstocks are excluded before application. – Projects are cancelled or adjusted if soil or rock quality falls outside the optimal range, avoiding contamination or inefficiency. – Focus is placed on preventive rather than corrective measures through continuous site	The academic literature points out similar concerns regarding the environment (Levy et al. 2024)

Topic/Parameter	Broad Consensus (Majority View)	Differing Opinions / Unique Perspectives	Literature support
	ecosystems and causes habitat loss. – Transport-related externalities such as air pollution, traffic congestion, and noise from diesel vehicles add indirect environmental and social burdens.	assessment and exclusion criteria.	
	Mitigation and Control Measures – Universal agreement that PPE use (masks, dust coats, safety glasses) is essential to protect workers during handling and spreading. – Strict feedstock testing is required to ensure heavy metals remain below permissible thresholds, using recognized ISO/ASTM sampling standards. – Promote among farmers the use of	**Adaptive Management Practices** – Instead of relying primarily on lab-based mitigation, some adopt field-level adaptive management, such as using buffering agents to stabilize low-pH soils and maintain optimal carbonic acid balance. – Emphasis is placed on real-time environmental feedback, allowing quick correction if chemical or biological imbalances emerge.	

Topic/Parameter	Broad Consensus (Majority View)	Differing Opinions / Unique Perspectives	Literature support
	plants that take up heavy metals – Dust suppression (e.g., moistening materials, covering loads, avoiding high-wind application) is a best practice for air quality control. **Application Practices to Reduce Dust”** – Use of lime-spreading equipment designed to place mineral into soil rather than air. – Application on non-windy days to minimize dust dispersion. **Risk Considerations:** – Mineral may not harm land but can affect people if inhaled or contacted directly. Dust containing minerals such as quartz may pose respiratory silica hazards.	• This approach supports flexible, site-specific environmental safeguards over rigid standardization.	

Topic/Parameter	Broad Consensus (Majority View)	Differing Opinions / Unique Perspectives	Literature support
	– Avoid creating airborne plumes. – Optimized transport logistics and use of low-emission vehicles can reduce indirect pollution and energy use. – Regular soil and water monitoring post-deployment is recommended to track potential toxic element build-up or leaching.		
	Observed Challenges and Learnings – Past ERW projects have reported toxic runoff and metal contamination, leading to project shutdowns (e.g., UK basalt/olivine case). – These incidents underscore the need for robust quality assurance and continuous	**Positive Empirical Outcomes** – Some recent ERW deployments (e.g., in tropical agricultural regions) have not shown measurable contamination or degradation, suggesting that responsible sourcing and monitoring can effectively mitigate environmental threats. – Proponents of this view argue that well-planned	

Topic/Parameter	Broad Consensus (Majority View)	Differing Opinions / Unique Perspectives	Literature support
	environmental oversight. – Experts agree that poor-quality rock or improper application rates remain the leading causes of environmental risk and project failure. – There is shared acknowledgment that social license to operate depends on maintaining environmental safety and transparency.	projects inherently avoid high-risk conditions, reducing the need for extensive post-facto mitigation.	

- Cost considerations

Topic/Parameter	Broad Consensus (Common Views)	Differing Opinions / Unique Perspectives	Literature support
Cost Considerations	**Cost reduction through local and low-cost operations:** – Most agree that ERW projects become more viable in countries with lower labour and operational costs (e.g., India, Kenya, China), as	**Farmer-benefit model:** – Some projects provide basalt to farmers free of cost, allowing them to retain all agricultural benefits while the implementing organization keeps carbon credits to sustain operations—	Both the majority and minor perspectives is reflected in the literature (Beerling et al. 2024).

Topic/Parameter	Broad Consensus (Common Views)	Differing Opinions / Unique Perspectives	Literature support
	sampling and field activities are significantly cheaper than in developed regions.	focusing on social and economic co-benefits rather than cost recovery through credit sales.	
	Use of waste or by-product materials: – Commonly recommended to utilize industrial silicate dust, quarry waste, or other alkaline by-products instead of freshly mined rock. This reduces both material procurement and processing expenses.	**Focus on agricultural yield improvement:** – Some emphasize that the key economic advantage of ERW lies not just in carbon credits but in enhanced soil fertility and crop yield (reported 25–30% increase per season), indirectly offsetting overall project costs.	
	Lower MRV costs through simplified parameters: – There is agreement that using soil agronomic indicators instead of expensive analytical instruments (ICP-MS, XRF, XRD) can make MRV more	**Integrated cost-benefit approach:** – Certain perspectives highlight that optimizing internal ERW processes—like particle size, soil targeting, and process integration—can simultaneously improve efficiency and reduce costs, offering an	

Topic/Parameter	**Broad Consensus (Common Views)**	**Differing Opinions / Unique Perspectives**	**Literature support**
	affordable without losing reliability.	endogenous way to improve economics. – Partnering between ERW project developers and feedstock supplier can help to reduce initial investment, with the supplier bearing the cost for transport and rock supply initially; post credit sale, the profit maybe shared	
	Carbon credit pricing remains high: – Broad consensus that current costs (~\$400/ton CO_2) are high but can reduce to \$250–\$280/ton with scaling and efficiency improvements.	**Dependence on external economic conditions:** – Some highlight that external factors (fuel prices, interest rates, labor/energy costs) can significantly influence total project cost, independent of ERW process design.	
Compensation and Responsibility	**Remediation responsibility:** – Poor ERW practices are considered potentially remediable, and companies may	**Compensation mechanisms remain unclear:** – There is no established approach for compensating farmers if soil quality is	

Topic/Parameter	Broad Consensus (Common Views)	Differing Opinions / Unique Perspectives	Literature support
	include contractual provisions to address severe negative impacts. – Need for policy and research: There is a clear need for further scientific and policy research on soil remediation strategies and farmer compensation mechanisms.	negatively affected by excessive rock dust. – Possible mitigation options (still uncertain): Potential responses may include soil removal, additional soil amendments, or crop changes, though these require further investigation.	

3.7 Stakeholder Consensus on Best Practices

- Rock Type Preferences

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
Rock type	– The choice of rock type is site and project specific. Also, it depends on weathering kinetics and transport-deployment cost. – Basalt is generally the most preferred rock type for ERW. Most authors have indicated this rock type to be the most suitable. Some	– Olivine and wollastonite were also mentioned by some experts as alternatives. – Olivine is considered suitable due to its high weathering rate and rich magnesium content.	All the stated views can be found being reflected across the academic literature (Manning,

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	experts even pointed out the following reasons for its selection: – It is widely available, particularly in countries like India (Deccan Plateau). – It supplies essential macro- and micronutrients (Ca, Mg, Fe, Si), supporting both carbon removal and soil fertility improvement. – Avoid rocks containing high concentration of potential toxic elements and sulphide minerals should be avoided due to the risk of contamination. Basalt poses lower risks of heavy metals or toxic elements compared to some other rocks. – Though basalt weathers slower than olivine or wollastonite, it offers a better balance of co-benefits. – It is especially useful in regions with degraded soils,	– However, experts caution that both olivine and wollastonite require strict quality control due to potential contamination from toxic elements (heavy metals, etc.). – Some expert noted that olivine is often proposed but did not compare its performance directly with basalt. – Olivine is less abundant than basalt, and also has risks associated with asbestos/serpentinite (unsuitable for farm application; may only be used at mine sites in tailings piles). – Wollastonite is mono-mineralic and free of most contaminants, meaning it lacks the broad nutrient profile of basalt, offering fewer agronomic benefits. Its distribution is also limited.	2002; 2025; Dupla et al. 2024)

Topic/Parameter	**Broad Consensus (Most Experts)**	**Diverging Opinions (Other Expert Views)**	**Literature Support**
	such as Southeast Asia and Africa. – Rock powders may be sourced from civil construction and gravel companies, which produce excess material as waste. Using this would create a circular economy model that reduce waste and lowered farm input expenses (e.g., as practices in Brazil).	– Wollastonite also lacks good detrital tracer hindering MRV. – One of the stakeholders also pointed out that basalt is preferred as it is cheaper compared to olivine and wollastonite. – One stakeholder suggested to prioritize zero-emission 12-micron M-sand basalt slurry by-product from construction wash tanks, diverting from landfills to eliminate mining emissions. But slurry extraction and drying should be accounted for in LCA. – One of the stakeholders suggested limestone or agricultural lime can be used as a ERW feedstock. Dissolution of lime by carbonic acid converts CO_2 to bicarbonate, which can act as a temporary carbon sink. While dissolution by strong acids (e.g., nitric or sulfuric acid) releases CO_2, raising	

Topic/Parameter	**Broad Consensus (Most Experts)**	**Diverging Opinions (Other Expert Views)**	**Literature Support**
		uncertainty about whether lime acts as a carbon source or sink. – Besides those, steel slag, fly ash and glacial rock flour also explored as feedstocks depending upon their suitability based on major controlling factors of ERW.	

- Application methods

Topic/Parameter	**Broad Consensus (Most Experts)**	**Diverging Opinions (Other Expert Views)**	**Literature Support**
Application Methods	**Grain Size and Weathering Efficiency** – Most experts agree that smaller grain sizes accelerate weathering, but extremely fine particles (<10 µm) are impractical due to high energy costs, dust hazards, and difficulty in field application. – The optimal range of 50–100 µm offers a good	**Some nuanced or extended perspectives were noted:** – One expert mentioned that ultra-fine grinding (<10 µm), though energy-intensive, may be justified in short-term demonstration projects seeking rapid CO_2 removal despite higher costs.	The current global academic literature identifies all this points but also points to the need of further research (Dupla et al. 2024; Vandeginste et al. 2024)

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	balance between effectiveness and operational feasibility, achieving near-complete weathering within about 10 years. – Experts suggest below 100 µm grain size shows good promise for fast weathering **Local Rock Sourcing and Transportation Limits** – Strong consensus that ERW projects should use regionally sourced rocks, ideally within 100 km of deployment sites. Stakeholders point out due to lower CDR rates of basalt (compared to olivine, wollastonite, etc.) it requires the use of high mass volume and distances not greater than 100-150kms from quarry. – Long-distance transport significantly increases costs and reduces net	– Another stakeholder also mentioned that a quarry-sourced particle size ≤5 mm is considered practical and energy-efficient, while still providing substantial ERW weathering benefits. Additional screening to <2 mm or <1 mm may improve modelling accuracy and potentially enhance reaction effectiveness, though it requires further processing. – A rare case was cited where international rock transport (using biofuel-powered shipping) was explored to offset emissions—though experts largely view this as impractical for large-scale operations. – Slight operational variations exist in how waste rock is prepared (sieving, analysis, or	

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature Support
	carbon benefits by worsening the Life Cycle Assessment (LCA). – Using locally available feedstock (e.g., Deccan or Rajmahal Traps for basalt) is therefore considered the most sustainable and climate-positive approach. **Preference for Waste Rock** – Experts broadly agree that waste rock or crusher by-products should be used instead of freshly mined materials to minimize additional emissions and avoid encouraging new mining activities.	direct deployment), but these do not deviate from the overall consensus that using local waste rock within 100 km remains the best practice for ERW scalability and sustainability. – Experts suggest, olivine and wollastonite due to their high CDR rates, they require movement of less mass volume and can be used over large distances. – Due to their higher CDR rates, they may be used over long distances, specially using transportation methods like barging (low cost/low emission). But such methods of transportation are limited and not widely available. – On-site tractor piling may be used followed	

Topic/Parameter	**Broad Consensus (Most Experts)**	**Diverging Opinions (Other Expert Views)**	**Literature Support**
		by low-emission manual labour spreading for net reduction.	

- Geospatial and Ecosystem Suitability

Topic/Parameter	**Broad Consensus (Most Experts)**	**Diverging Opinions (Other Expert Views)**	**Literature support**
Geospatial and Ecosystem Suitability	**Preferred Ecosystem: Croplands** – Most experts agree that agricultural croplands are the most promising ecosystems for ERW implementation due to high soil pCO_2, acidic conditions (mainly in tropical climates) and less lag in soil cation absorption. – Croplands allow ease of integration with existing practices (e.g., replacing liming agents). Most experts agree that following current agricultural practices is beneficial for ERW	**Differing or Additional Perspectives** – One expert emphasized that while croplands are the main focus, rice paddies may be *particularly efficient* for ERW because stagnant water enhances carbonic acid formation and basalt weathering rates. – Suggested that rice-based systems (e.g., in central India, Madhya Pradesh, Chhattisgarh) offer faster CO_2 sequestration and higher cost efficiency	Currently there is a dearth in research studies investigating the suitability of different ecosystems for ERW. Although their suitability for tropical agricultural croplands is generally accepted (Beerling et al. 2018)

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature support
	scalability and feasibility. But they also point out that practices like tillage and ploughed system affect soil carbon; the effects of which are still not well understood. – They provide co-benefits such as improved soil fertility, soil pH reduction, crop productivity, and simplified monitoring after harvest. – ERW on croplands also facilitates sampling and MRV (Monitoring, Reporting, Verification) processes, making it suitable for carbon credit certification. **Unsuitable or Challenging Ecosystems** – Forested areas and mountainous regions are largely unsuitable due to difficulty in sampling,	compared to dryland or long-cycle crops like sugarcane. – Highlighted that short-cycle crops (e.g., paddy, pulses, groundnut) enable repeated basalt use, increasing cumulative sequestration. – Another expert observed that regional variation in ERW adoption (e.g., U.S. Midwest vs. coastal areas) may reflect agricultural concentration, not purely geological suitability. – Proposed use of isotopic fingerprinting ($\delta^{13}C$) to better distinguish carbon sources and improve MRV precision in Indian conditions. – One expert also mentioned that while	

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature support
	high runoff, and poor MRV feasibility. – Environmentally sensitive zones, including highly alkaline soils, are avoided since ERW's pH-driven weathering mechanism becomes ineffective. – High soil pH favours carbonate precipitation resulting in low CDR potential, low pH favours bicarbonate formation supporting higher CDR potential. For carbon credits, the latter is more preferable. – Areas with high background toxic element concentration (e.g., arsenic, heavy metals) should be excluded to prevent ecological and food-chain risks. Also, areas with high sulphur content in soil should be avoided.	natural ecosystems could theoretically benefit from ERW, empirical evidence remains limited, calling for further research beyond agricultural settings. – One of the stakeholders also explained that managed ecosystems such as forest plantations and palm oil systems, along with green infrastructure and selected civil engineering–adjacent areas (e.g., trial applications near airfields or runways), may serve as potential sites for ERW deployment based on trial experiences. – Pasturelands and forests are also potential candidates. But forests, have the slowest dissolution	

Topic/Parameter	Broad Consensus (Most Experts)	Diverging Opinions (Other Expert Views)	Literature support
	Geospatial & Soil Suitability Factors – Experts agree that site-specific soil conditions (pH, soil composition, nutrient profile) critically influence ERW success. – Dense loamy soils lead to binding of cations to soil exchange sites, resulting in delayed carbon removal; sandy soils – less cation retention, faster carbon removal. – Flat terrains and plains are preferred for operational ease and controlled water flow. Elevation may act as an indirect factor, with hilly regions resulting in higher rainfall in the windward side of the mountain, effects on temperature due to cooling, etc. – Local basalt availability (within ~100 km)	rates, followed by pasturelands. Also, these land types provide less agronomic benefits. – One of the stakeholders suggested a minimum of 1000mm rainfall per year for ERW to be suitable. – Although direct experimental evidence is limited, studies from Brazil suggest that rock dust applications in ERW process may help improve degraded land quality, potentially restoring habitats and enabling conversion into pasture or other ecological uses. – In terms of ecological consideration, application is more appropriate in areas	

Topic/Parameter	**Broad Consensus (Most Experts)**	**Diverging Opinions (Other Expert Views)**	**Literature support**
	enhances project feasibility and maintains a favorable Life Cycle Assessment (LCA). **Climatic and Biogeochemical Conditions** – Warm, humid, and high-rainfall regions accelerate weathering and enhance CO_2 uptake. – Degraded agricultural soils benefit most from basalt application due to micronutrient enrichment and improved soil structure.	where habitat is already degraded due to prior land-use change, supporting habitat recovery rather than disturbing intact ecosystems.	

- Scientific and Life Cycle Considerations

Topic/Parameter	**Broad Consensus (Majority View)**	**Differing Opinions / Unique Perspectives**	**Literature support**
Scientific & LCA Considerations	**Ideal Conditions for ERW** – ERW is most effective in warm, humid, tropical climates (e.g., India,	**Unique Environmental Insights** – One view stress avoiding deployment in alkaline or metal-	The views of the stakeholders are in agreement with the scientific

	Brazil, Kenya, Mexico) where high temperature and rainfall accelerate natural weathering and bicarbonate formation. – Works well in nutrient-poor, acidic soils (low pH) that promote silicate dissolution and CO_2 sequestration. – They also suggest that soil pH, cation residence time and bicarbonate flush rates as the essential factors affecting the effectivity of ERW. **– Fine grinding of silicate rocks (especially basalt)** increases reactive surface area, enhancing carbonation efficiency. **– Water availability** (e.g., in paddy systems) aids CO_2 dissolution and accelerates carbonic acid-driven weathering. **– Previous application of lime reduces CDR efficiency.** – Water draining into rivers or streams with **low**	contaminated soils, as these can suppress weathering reactions or mobilize toxic elements. – Water flowing into coastal zones with strong downwelling is preferred, as it helps in delaying equilibrium. **Crop Type Suitability for ERW** – Different perspective suggests that plants with large root systems are preferable.	literature (Beerling et al. 2024)

	aragonite saturation is preferred – higher concentration will lead to carbonate precipitation, resulting in 50% loss of CO_2. **Crop Type Suitability for ERW** – No specific crop type has been identified as significantly superior for maximizing ERW carbon sequestration, nutrient uptake, or soil interaction. – Differences in ERW effectiveness are more strongly linked to rock type rather than crop type.		
	Life Cycle Assessment (LCA) Considerations – Transportation distance is the most critical factor influencing LCA outcomes—keeping sourcing within ~100 km is key for maintaining net-negative emissions. Truck based transportation is the dominant factor in	**Expanded Assessment Frameworks** – Some experts emphasize integrating Techno-Economic Assessment (TEA) with LCA to evaluate trade-offs between cost, energy use, and CO_2 removal efficiency. – A few highlight that LCA should capture	

	transport related emission. – Grinding energy and feedstock extraction also contribute to emissions but are secondary to transport impacts. – Use of local quarry waste or crusher tailings minimizes upstream mining emissions and improves carbon balance. – Prefer train transport vs trucks, depends on electric vs diesel trains. – LCA boundaries consistently include feedstock preparation, transport, spreading, and sampling activities. – Some of the captured carbon is lost before final precipitation in ocean - limiting the amount of long-term carbon storage.	indirect effects (e.g., fertilizer use changes, N_2O fluxes) and use hybrid models linking environmental and economic data. – Quarrying has a lower energy demand per tonne, compared to grinding – energy costs increase exponentially below 100 microns. – Across multiple LCA's upstream emissions reduce overall carbon effectiveness by ~10%.	
	Field Evidence and Best Practices – Field deployments in India and other tropical zones show improved soil	**Comparative Observations** – Empirical evidence suggests Indian tropical systems outperform	

	health, higher bicarbonate flux, and long-term CO_2 sequestration over multiple crop cycles. – Multi-season monitoring and local crusher engagement are encouraged for sustainability and circular-economy benefits. – Maintaining transparency and data sharing supports MRV readiness and future carbon market certification.	temperate-region trials in CO_2 removal and nutrient enrichment, highlighting the need for region-specific calibration rather than universal baselines.	

3.8 Stakeholder Consensus on Legal and Regulatory Barriers

- Legal and Regulatory Barriers for ERW

Topic/ Parameter	**Broad Consensus (Common Views)**	**Differing Opinions / Unique Perspectives**	**Literature support**
Legal & Regulatory Barriers	**Need for clear national policy and regulatory framework:** – Most stakeholders emphasize that India currently lacks a dedicated	**Project-level coordination model:** – Some stakeholders note that even without a national policy, effective implementation can	The present policy literature also highlights the issues pointed out by the stakeholders

Topic/ Parameter	Broad Consensus (Common Views)	Differing Opinions / Unique Perspectives	Literature support
	ERW policy, making implementation and credit recognition difficult. – A formal national guideline could define standards, support mechanisms, and integration with climate and agricultural frameworks. **Requirement for legal and administrative clearances:** – Common understanding suggests that ERW projects require clearances related to quarrying, environmental standards, and land-use permissions—often involving agreements with farmers or local authorities. – Land titles are foundational for effective ERW policy implementation. Clear and secure land tenure is essential.	proceed through strong coordination with state and district authorities, using MoUs and local administrative engagement to ensure legitimacy and compliance. **Collaborative academic partnerships:** – A few projects emphasize that formal collaboration with government universities and state agriculture departments serves as both a compliance and research validation mechanism, ensuring transparency and data sharing with government institutions.	(Johnstone et al. 2025; Dörpmund, 2025)
	Urgent need for carbon credit regulation and cost-effective registry systems: – Broad consensus that existing international	**Localized governance and monitoring practices:** – Some stress that ongoing local	

Topic/ Parameter	Broad Consensus (Common Views)	Differing Opinions / Unique Perspectives	Literature support
	registries are expensive and unsuited for Indian developers. A national carbon credit certification or registry system is required to make ERW financially viable and reduce dependency on global platforms. **Regulatory oversight for MRV and credit integrity:** Most agree that an official MRV and certification mechanism is necessary to prevent double counting and ensure credibility in carbon accounting, ideally under government or authorized scientific bodies. Issued credits should meet core integrity criterions like permanence, leakage, no double counting, etc. Responsibility must be clearly assigned to ensure these criteria are met across the value chain.	engagement—through district authorities, panchayats, and agriculture officers—can substitute for top-down regulations by ensuring community trust, administrative oversight, and smoother implementation. **Incremental recognition approach:** – While most call for new policies, a few advocates first embedding ERW within existing agricultural or climate frameworks (similar to Biochar) before developing a standalone national policy.	

- Stakeholder coordination and policy

Topic/Parameter	Broad Consensus (Common Views)	Differing Opinions / Unique Perspectives	Literature support
Stakeholder Coordination & Policy Alignment	**Need for multi-stakeholder coordination platforms:** – Broad agreement that ERW mainstreaming requires collaboration between researchers, developers, policymakers, and local communities (both large scale and small-scale landholders) to form policy, standardize practices, and enhance credibility. – Avoid polarisation among the various stakeholders and provide equal importance without favouring any specific group. Experts suggest, getting everyone onboard and to undertake constructive engagement to develop policy. Although this is difficult, but necessary.	**Localized and phased engagement model:** – Some emphasize starting coordination at the *grassroots level*—with farmers, panchayats, and local leaders—before expanding to higher-level policy or national platforms. **– Independent, demonstration-first approach:** A few focuses more on *field-based validation* and community-led expansion ("word-of-mouth diffusion") rather than formal coordination platforms or institutional partnerships. **Communication focused on co-benefits over carbon markets:**	The present policy literature also highlights the issues pointed out by the stakeholders (Johnstone et al. 2025; Dörpmund, 2025)

	– Maintain balance between regulation and ease of doing business. Prevent powerful actors from lobbying for exemptions. Ensure environmental accountability applies fairly. **Collaboration with credible ERW actors:** – Consensus that established Indian organizations (e.g., Alt Carbon, Mati Carbon) play a key role in convening meetups, building networks, and strengthening implementation linkages. **Policy design must be science-based and farmer-centric:** – Most stakeholders agree that ERW policies should be grounded in scientific evidence, supported by controlled field trials, and directly benefit farmers through improved soil health, productivity, and	– Some practitioners deliberately emphasize soil fertility and yield gains instead of carbon credit revenues to build farmer trust and participation. **Integration with existing agricultural and soil programs:** – Instead of a separate ERW policy, a few argue for embedding ERW within current government soil health and climate resilience schemes to accelerate adoption and policy acceptance. **Philanthropy-driven coordination models:** – Some initiatives operate entirely through philanthropic or grant-based funding (e.g., XPRIZE, Frontier), prioritizing social good and open data sharing over commercial or policy-driven coordination.	

	fair carbon revenue distribution. – Local governing bodies should be involved in decision-making processes. Even if not directly issuing permits or regulations, they should play a meaningful role in the broader governance ecosystem and provide an accessible channel for farmers to raise concerns. **Built-in Monitoring and Evaluation (M&E):** – Policy frameworks should include scheduled evaluations (e.g., 3, 5, 10 years), mechanisms for revision and improvement as continuous review improves effectiveness over time **Creation of a national ERW policy and domestic carbon credit registry:** – Strong consensus that India needs a dedicated ERW policy framework at the federal level to enable		

	in-country credit trading, retain financial benefits domestically, and ensure equitable farmer participation. **Transparency and verification are central to stakeholder trust:** – Common understanding that MRV-backed, science-informed data sharing enhances buyer confidence, reduces greenwashing risks, and builds long-term credibility across the ERW ecosystem. **Independent Evaluation with Accountability:** – Evaluations should be independent from implementation bodies and financing entities. They should not be employed by or directly part of the government. Their sole responsibility should be: Assess whether projects meet predefined criteria.		

	– Currently, there is a lack of high-quality carbon credit market. The above steps ensure India generate high quality carbon credits. – Link funding or credit issuance to completion of evaluations. Make evaluation outcomes consequential. – Strong policy frameworks involving institutional checks and balances are required to enhance market credibility – Policy must ensure there are transparent public institutions that enforce checks and balances on one another. Simply passing a law is not sufficient. – Effective implementation requires involvement of: Executive branch (implementation) and the financial sector (financing, regulation, standardization).		

	– Secure Free-Prior-Informed Consent from farmers and ensure farmer autonomy **Public Disclosure & Transparency in Carbon Projects:** – Auditor reports should be submitted to the government. – Project data should also be accessible to academics, governments, communities, competitors, and the broader public. – Publicly available data should include the following: Baseline data and justification for baseline selection; post-implementation monitoring data (e.g., year-one results); raw data used in calculations; project reports; project proponents; methodologies used to calculate carbon sequestration. – GIS coordinates should be provided for each data		

	type (allowing satellite verification). **Farmer incentives and cost structure:** – Effective ERW policy should prioritize improvements in crop yield and soil health as primary incentives for farmers, while companies assume the financial and technical responsibilities associated with MRV, which farmers generally cannot afford. **Policy and implementation model:** – The Brazilian approach demonstrates scalable ERW deployment through regulatory approval by agricultural authorities (e.g., Embrapa), with multiple registered ERW products and large-scale annual applications. **Adoption pattern:** – Current uptake is mainly among commercial crop producers serving domestic markets, while		

	large export-oriented agribusiness sectors continue to rely largely on chemical fertilizers. **Policy integration with agriculture and climate goals:** – ERW policies can be aligned with programs aimed at reducing fertilizer and liming use, potentially delivering climate benefits by lowering CO_2 emissions associated with limestone-based practices and encouraging a shift toward silicate materials. **Economic trade-offs:** – Reducing limestone use could affect related industries, requiring careful economic balancing, while increased silicate mining may help offset emissions and sustain employment.		

	Land governance and benefit distribution: – Unclear land ownership and lack of accessible land title records create challenges in voluntary carbon markets, leading to uncertainty over benefit distribution and risks of communities not receiving promised returns. **Policy priority:** – Clear land title regulation and strong land governance frameworks are essential to ensure fair benefit-sharing, effective policy implementation, and prevention of disputes or exploitation. **Linking Voluntary Carbon Markets to Nationally Determined Contributions (NDCs):** – Voluntary carbon markets can support countries in progressing toward their NDC targets under the Paris Agreement and may encourage		

	behavioural and sectoral changes in emission reduction strategies. **Key limitations:** – Carbon markets cannot serve as the sole pathway for achieving NDCs. – Meeting national climate commitments requires large-scale institutional reforms, structural economic transformation, and a shift away from fossil-fuel–based growth models.		

CHAPTER 4 - REPORT ON CURRENT ERW PRACTICES AND SCALABILITY

4.1 Current global practices for ERW

This section synthesises findings from published literature and the stakeholder engagement done as part of the current project. The number of studies that undertakes an overall life cycle assessment of the ERW process is limited. In this section, we discuss the current global practices with reference to the Life Cycle Assessment of an ERW project. An in-depth life cycle assessment (LCA) is essential to quantify ERW's net carbon benefit, identify environmental trade-offs, and understand scalability. LCA provides a framework to assess the cradle-to-grave environmental impacts of ERW, accounting for all inputs and outputs, from rock extraction to carbon sequestration verification. The LCA has been discussed across four sub-sections namely, 'mining/extraction', 'transportation and logistics', 'spreading and field application' and 'monitoring, reporting, verification'. The various protocols currently in place for CDR with respect to ERW has also been discussed in this section along with the safety and security aspects of ERW.

4.1.1. Mining/Extraction

The ERW life cycle begins with sourcing silicate minerals, typically basalt and olivine, known for their high weathering reactivity. Site selection and material choice significantly shape the environmental footprint. The mining process includes initial overburden removal, blasting, hauling, and crushing to produce fine powders optimized for rapid weathering (Fig. 4.1). The net carbon emissions from mining constitute an important denominator in the overall ERW equation. Lefebvre et al. (2019) found mining emissions (including blasting, loading and crushing) in São Paulo (Brasil) to represent roughly 30% of the total CO_2 removals (Fig. 4.2) (GHG balance; IPCC, 2014) attributed to weathering the applied rock mass; indicating that while significant, emissions can be managed to maintain net carbon negativity.

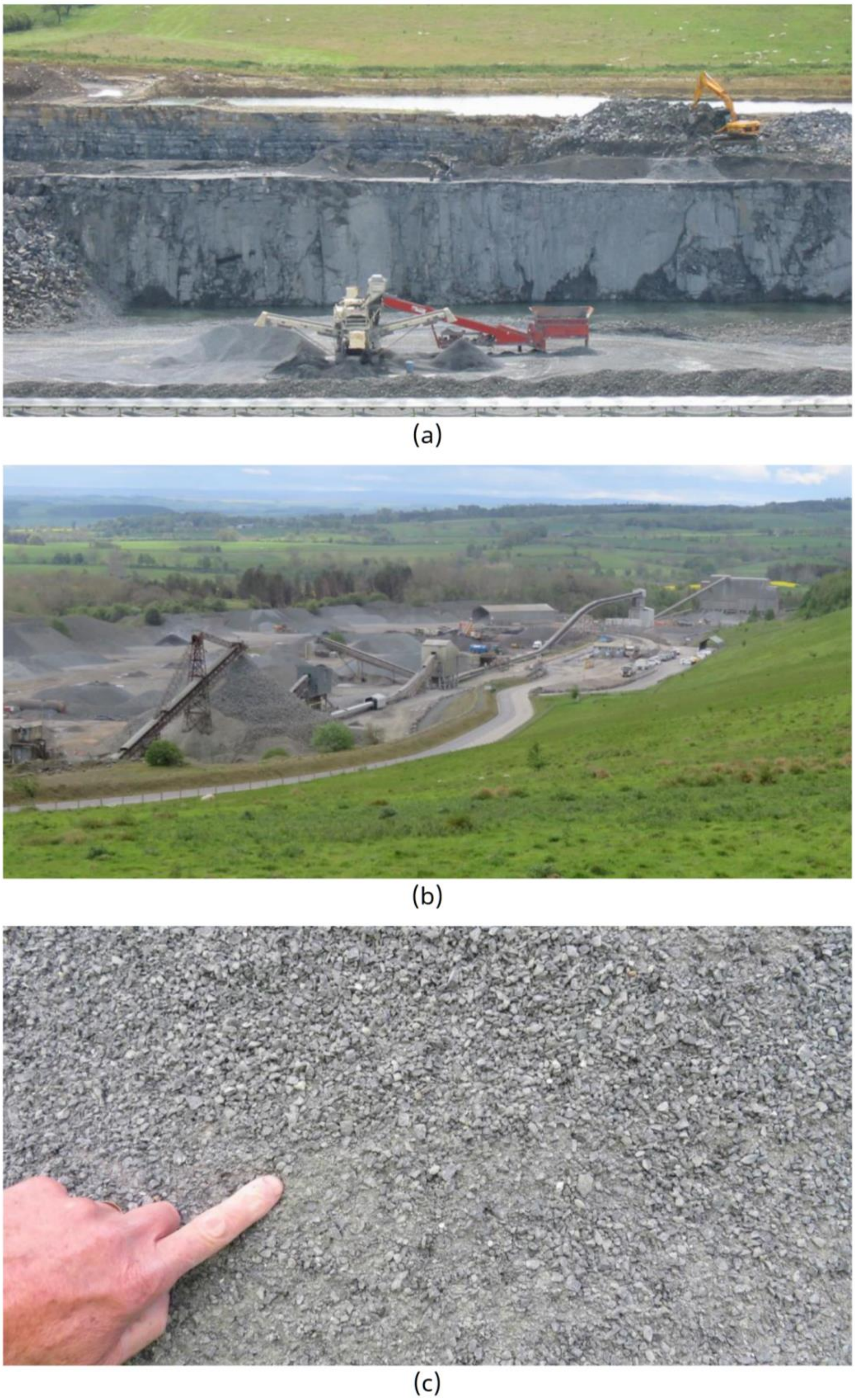


Fig. 4.1: (a) Typical mining operation that extracts rocks which may be used, or mine tailings which may be used for ERW (b) Crushing operations that grind the mined rocks (c) Typical size of quarry fines used for ERW (reproduced from Manning, 2025)

Crushing or comminution to particle sizes often less than 100 microns requires substantial energy. While finer grain sizes facilitate faster weathering, it also leads to an increased carbon footprint due to the energy requirement of grinding. This carbon footprint maybe reduced by the use of renewable and green energies for the process. For example, Fig. 4.3 shows a plot of how upstream carbon intensity changes with respect to different grain sizes from (Breunig et al., 2024), with electricity sources considered for Northern California (USA). The points (in Fig. 4.3) represent electricity from various electricity utility companies along with the type of energy used to generate that electricity. As can be seen in the diagram (Fig. 4.3), use of electricity from wind energy (blue dots) as opposed to electricity generated from natural gas (yellow dots) significantly reduces the amount of upstream carbon intensity, especially with decreasing grain size.

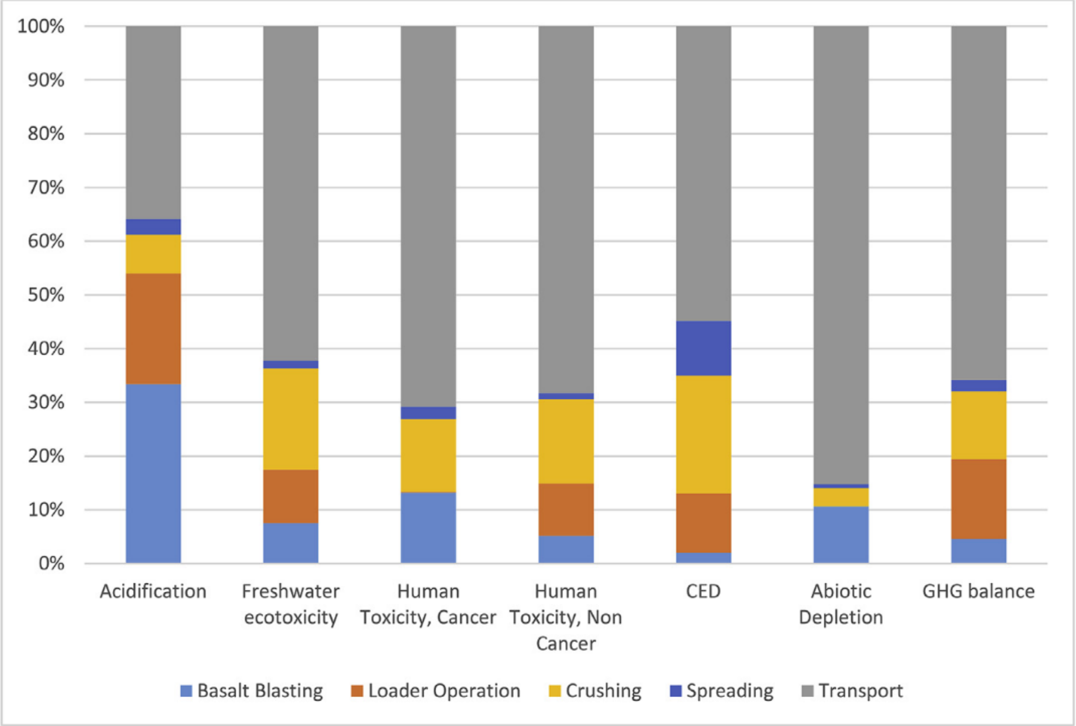


Fig. 4.2: Diagram showing the proportion of each stage of ERW on different impact categories as studied in Lefebvre et al. 2019 (reproduced from Lefebvre et al. 2019; see Lefebvre et al. 2019 for more details).[CED – Cumulative Energy Demand; GHG – Greenhouse Gas]

Environmental risks associated with mining include land disturbance, dust emissions, and potential release of potentially toxic elements (PTEs) such as Ni and Cr from basalt minerals (Dupla et al. 2025). Studies and stakeholder views emphasize monitoring and management of these elements to prevent soil and water contamination. Responsible sourcing protocols mitigate these risks by prioritizing quarry waste reuse and limiting mining in ecologically sensitive areas. Material efficiency can also be improved by utilizing quarry fines and mine tailings rather than virgin rock. This reuse reduces the embodied energy and emissions associated with mining and grinding (Zhang et al., 2023).

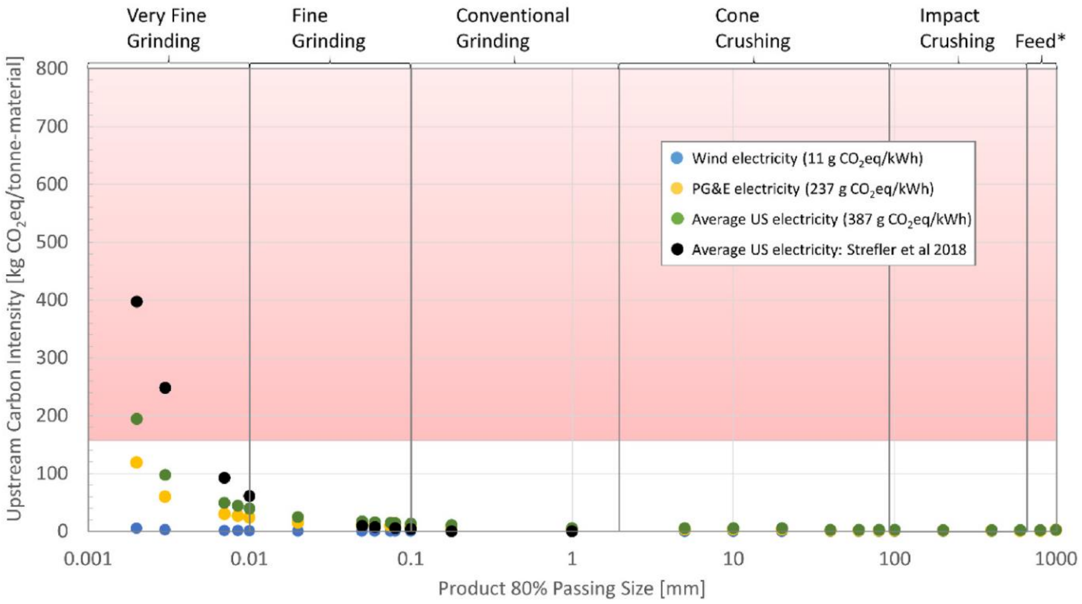


Fig. 4.3: Upstream carbon intensity associated with grinding silicate rocks to different particle sizes. Particle size of the grinding operations consider 80% passing size. Source of different electricity is also considered. The area marked with red shows the region where no life-cycle carbon removal can take place based on the ERW potential of meta-andesite [PG&E – Pacific Gas and Electric, USA; * - Quarry blasting assuming emissions from limestone mining] (reproduced from Breunig et al. 2024)

4.1.2. Transportation

Once crushed and milled, the rock powder must be transported to application sites, often covering considerable distances. Transportation emissions typically represent one of the largest operational carbon costs in any ERW project (Lefebvre et al. 2019). (Moosdorf et al., 2014) reported an average emission related to transportation ranging between 0.007t

CO_2 t^{-1} [optimistic scenario] and 0.022 t CO_2 t^{-1} [pessimistic scenario], in their global assessment.

Lefebvre et al. (2019) quantified these emissions for São Paulo, estimating more than 60% of the GHG balance being due to transportation for distance of 65 km by diesel trucks. This figure corroborates other studies that highlight the sensitivity of ERW's carbon balance to transport logistics. Road transport is less efficient than rail or barge but is often unavoidable due to infrastructure and geography (Beerling et al. 2020).

Additional factors influencing transportation impacts include fuel type, vehicle load factors, and backhauling opportunities. Leveraging electrified or biofuel-powered fleets and integrating ERW logistics with existing agricultural supply chains can markedly reduce emissions. The environmental footprint of transportation extends beyond carbon emissions. Diesel vehicle exhaust contributes to particulate matter and nitrogen oxide pollution, presenting health risks for communities along transport corridors. Noise and traffic congestion are additional social considerations requiring mitigation and stakeholder engagement. A strategic focus on local sourcing of rock materials is essential to minimize transportation distances and associated emissions. Stakeholder engagement and literature review suggests a maximum distance of ~100 km to be best suited to balancing the carbon emission from transport with the CO_2 removal potential of ERW.

4.1.3. Spreading

The application phase involves spreading finely milled rock powder onto agricultural fields, usually employing modified fertilizer spreaders mounted on tractors. This stage encompasses several emission dimensions: type of fuel used in the spreading machinery, the speed and time of operation, area of application, etc. Efficient machinery uses and minimal soil disturbance practices can reduce emissions (Beerling et al. 2020; Lefebvre et al. 2019). Timing and weather conditions for spreading are carefully managed to decrease dust emissions and maximize mineral-soil contact. Currently, most ERW projects employ the local spreading machinery that was used under business-as-usual scenarios to reduce their carbon footprint. Also, steps have to be taken to ensure no post spreading runoff or remobilization by wind or water occurs.

4.1.4. Protocols

Robust MRV systems underpin credible ERW projects, ensuring operational transparency and enabling broader participation in carbon markets. MRV involves baseline soil and

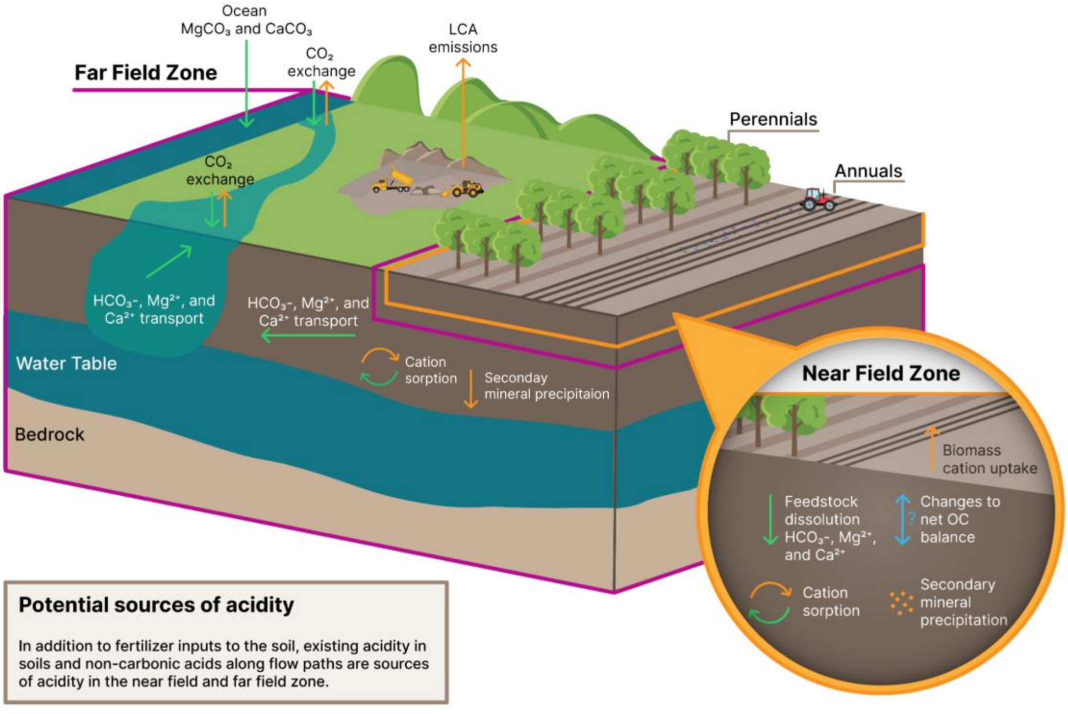


Fig. 4.4: Estimation of CDR rates, emissions and loss of CO_2 for ERW are undertaken across the Near Field Zone and Far Field Zone in current MRV protocols (reproduced from Mills et al. 2024).

water sampling, ongoing monitoring of carbon stocks, verification of mineral source origin, transport emissions accounting and third-party audits, among others. Recent studies emphasize the need for region-specific calibration of weathering rates and carbon retention models to avoid over- or underestimating net removals (Abdalqadir et al. 2024; Power et al. 2025). Current MRV protocols generally evaluate the effects and emissions related to ERW projects across three parts (Fig. 4.4) (Mills et al. 2024). The first of these is what is known as the Near Field Zone (NFZ). NFZ considers the top few centimetres of the soil profile. This is the zone where the initial reactions for carbon capture take place and generally involves studying the effects of ERW across the top soil horizons. Depending upon various factors like soil chemistry and tillage practices among others, this depth may vary from project to project. Most empirical measurements to quantify CDR from ERW projects take place in this zone. Following the NFZ, the net negative emissions and effects are considered along the Far Field Zone (FFZ). The FFZ begins from after the NFZ, and generally include the lower vadose zone and up to the groundwater table level. This zone also considers the downstream effects along the surrounding rivers and streams, leading to the ultimate storage of the removed carbon into the oceans. Current MRV protocols mandate the estimation of downstream losses along the FFZ, but the field based MRV approaches currently used, rely on empirical measurements mostly from the NFZ. Hence, MRV protocols currently rely on calculations done through modelling for estimating downstream CO_2 loss which are in some way informed from empirical data (Clarkson et al., 2024; Suhrhoff et al., 2025). Life Cycle Assessments (LCA) considers the emissions and effects from the ERW projects related to the stages of mining of feedstocks, grinding of the rock powders for application, transportation of ERW feedstocks, the process applying rock powders on the farmlands and other emissions related actions along the entire life cycle of the ERW project.

MRV protocols extends beyond CO_2 accounting to include risk management for heavy metals and dust, co-benefit reporting on soil health improvements, and social safeguards documentation (Fig. 4.5). Projects must demonstrate additionality—carbon removal beyond business-as-usual expectations—and avoid double counting across markets or temporal scales. Technological advances, including remote sensing, isotopic tracing, and blockchain-enabled digital ledgers, are increasingly leveraged to improve MRV accuracy, traceability, and integrity. Continuous innovation in MRV is leading to ERW projects delivering more verifiable climate impact alongside sustainable ecosystem benefits. Measurement techniques vary widely, and several researchers emphasize the importance of combining methods.

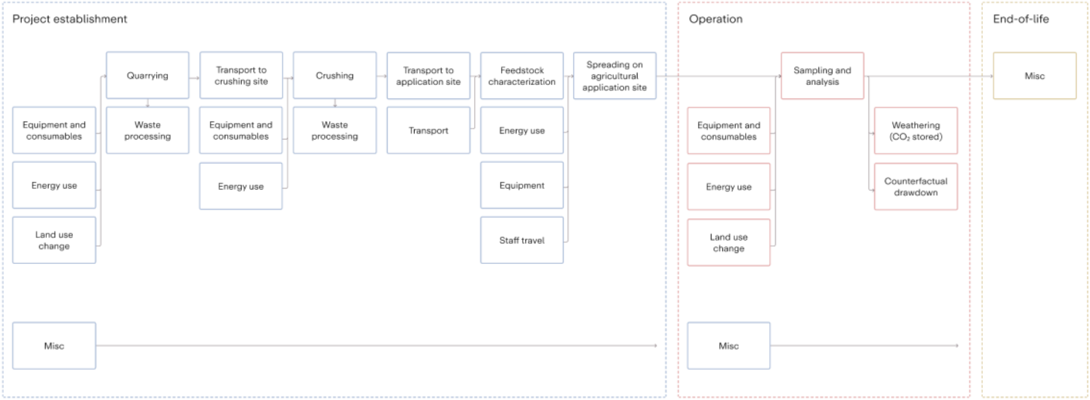


Fig. 4.5: Systems boundary and scope of activities to be included for ERW projects following the Isometric protocol. (reproduced from Isometric protocol for ‘Enhanced Weathering in Agriculture - v1.1’)

Currently, there are two main registries that have released protocols for MRV related to ERW – Isometric and Puro.Earth. International protocols, such as the Puro Standard and the Isometric registry outline comprehensive requirements spanning full life cycle accounting and project eligibility (Fig. 4.5).

The Isometric protocol measures the amount of CO_2 removed using the following formula:

$$CO_2e_{Removal,\,RP} = CO_2e_{Stored,\,RP} - CO_2e_{Counterfactual,\,RP} - CO_2e_{Emissions,\,RP}$$

RP -- Reporting period

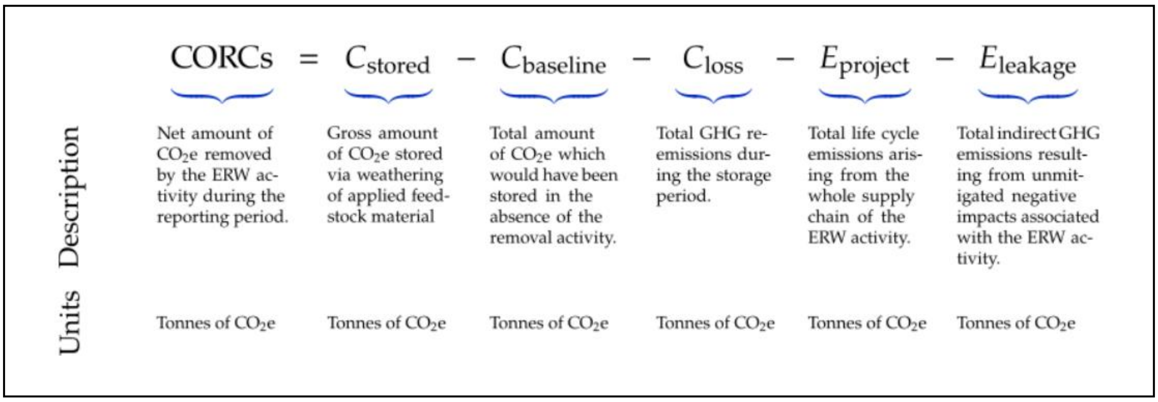
$CO_{2}e_{Removal,}$ *RP* -- the total net CO_2e removal for the Reporting Period, RP, in tonnes of CO_2e

CO_2e_{Stored}, *RP* -- the total CO_2 removed from the atmosphere and stored as inorganic carbon in the solid or aqueous form in the treatment and deployment (in 3-plot approach) plots for the *RP*, in tonnes of CO_2e.

$CO_2e_{Counterfactual}$, *RP* -- the total counterfactual CO_2 removed from the atmosphere and stored as inorganic carbon in the solid or aqueous form for the RP, in tonnes of CO_2e

CO_2eEmissions, RP -- the total GHG emissions for the RP, in tonnes of CO_2e

Similarly, for Puro.Earth – the amount of CO_2 removed is given by the formula:



$$\underbrace{\text{CORCs}} = \underbrace{C_{\text{stored}}} - \underbrace{C_{\text{baseline}}} - \underbrace{C_{\text{loss}}} - \underbrace{E_{\text{project}}} - \underbrace{E_{\text{leakage}}}$$

	CORCs	C_{stored}	$C_{baseline}$	C_{loss}	$E_{project}$	$E_{leakage}$
Description	Net amount of CO_2e removed by the ERW activity during the reporting period.	Gross amount of CO_2e stored via weathering of applied feedstock material	Total amount of CO_2e which would have been stored in the absence of the removal activity.	Total GHG re-emissions during the storage period.	Total life cycle emissions arising from the whole supply chain of the ERW activity.	Total indirect GHG emissions resulting from unmitigated negative impacts associated with the ERW activity.
Units	Tonnes of CO_2e	Tonnes of CO_2e	Tonnes of CO_2e	Tonnes of CO_2e	Tonnes of CO_2e	Tonnes of CO_2e

CORC -- CO_2 Removal Certificates

4.1.5. Safety and Security

Major safety and security safeguards are necessary for the large-scale deployment of ERW. Spreading activities of rock powders during ERW generate airborne dust which can pose inhalation risks, especially since respirable crystalline silica and trace PTEs may be present. ERW protocols mandate dust suppression techniques, respirator use for workers, and environmental monitoring to limit air quality impacts (Levy et al., 2024).

Environmental safeguards also address runoff and leaching concerns to ensure that trace metals within the rock do not contaminate surrounding water systems. Buffer strips and regular soil testing form part of integrated management plans ensuring long-term ecological safety. Environmental risk assessments focus on potential heavy metal mobilization from rock powders, especially nickel and chromium. Regular soil and water testing guide adaptive management to prevent bioaccumulation. Dust and particulate exposure are minimized through particle size control and engineering measures.

Worker health and safety protocols mandate use of personal protective equipment during mining, crushing, and spreading. Training programs and exposure monitoring reduce risks of chronic respiratory conditions. Community engagement is critical. Affected populations near quarries, transport routes, and spreading fields must be involved through transparent dialogues, risk communication, and benefit-sharing frameworks. Noise, dust, and traffic impacts require mitigation plans to maintain social license.

Water conservation and aquatic ecosystem safeguards complement soil protection to address potential leachate risks. Multistakeholder governance frameworks is necessary to ensure accountability and environmental justice considerations. Finally, carbon market data management necessitates secure, tamper-proof systems to uphold market confidence, prevent fraud, and ensure transparency.

4.2 Current status

4.2.1 Public Perception

Studies focusing on the acceptance of ERW in public is scarce for countries like India, Brazil, China, etc. (Schenuit et al. 2025). But globally some studies have attempted to evaluate the perception regarding ERW in the common public. Research show that compared to other CDR technologies, public perception of ERW across nations is generally more ‘neutral and muted’ (Carlisle et al., 2020; Cox et al., 2022; Wright et al., 2014). People tend to be more undecided and neutral towards ERW compared to other CDR technologies, with generally more people supporting the technology than opposing it (Pidgeon and Spence, 2017). Carlisle et al. (2020) even reported support for small scale field trials. It is interesting to note that, compared to other CDR technologies trustworthiness of science, the government and the industry is a crucial factor for public support for ERW (Cox et al. 2022).

Quantitative studies indicate that the framing of ERW is vital for public perception. Technologies which are presented as more ‘natural’ tend to be more supported by public (Corner and Pidgeon, 2015). A study on communities vulnerable to climate change indicate the strong sentiment among them that climate mitigation efforts should respond to and benefit the local needs instead of benefiting the distant elites (Carr and Yung, 2018). Studies have shown that the acceptability for CDR technologies like Bioenergy with Carbon Capture and Storage (BECCS) are directly related to the policies introduced to incentivise them (Bellamy et al., 2019). Therefore, the public perception of ERW may also vary depending on the location, stakeholders, policy and economic frameworks based on which the technology is deployed (Cox et al. 2022).

4.2.2 ERW – the science

Enhanced rock weathering (ERW) is an emerging carbon dioxide removal (CDR) approach that accelerates the natural weathering of silicate and carbonate minerals by spreading crushed rocks like basalt on agricultural lands (Manning, 2025). This enhances carbon sequestration by converting atmospheric CO_2 into dissolved inorganic carbon and alkalinity that eventually stabilize in oceans. ERW also improves soil alkalinity and fertility, potentially boosting crop yields. Although the scientific rationale is robust, the science remains in a constant state of evolution, with ongoing research striving to validate and optimize the technique across heterogeneous environments (Bijma et al., 2026).

Current ERW research employs mesocosm and pot experiments predominantly to control and measure weathering processes under semi-natural and lab conditions (Pogge Von Strandmann et al., 2025). Mesocosm experiments allow researchers to simulate natural ecosystems and assess weathering reactions, carbon capture, and ecological impacts with manageable variables, while pot experiments focus on soil-rock interactions and plant responses on a smaller scale. These experiments facilitate the quantification of sequestration rates and the development of methodologies like the TiCAT process to estimate initial carbon dioxide removal rates more accurately (Reershemius et al., 2023). However, such experimental approaches are limited in scope and duration, highlighting the critical knowledge gaps in long-term, large-scale field validation.

Despite the progress in mesocosm and pot studies, there is a notable lack of long-term field studies on ERW (Beerling et al. 2025). Field conditions add complexity with spatial and temporal variability in climate, soil, vegetation, and hydrological factors that influence weathering and carbon capture (Santos et al., 2023). The slow natural dissolution rates of minerals require extended monitoring, often spanning years to decades, which has not yet been comprehensively achieved. Consequently, the field currently faces challenges in both monitoring and modelling ERW outcomes at scale and over time (Power et al., 2025). This missing long-term field data contributes to ongoing debates about the technique's overall carbon removal effectiveness, scalability, and environmental safety. Thus, the science of enhanced rock weathering is continuously evolving as new data emerge from ongoing pilot projects worldwide.

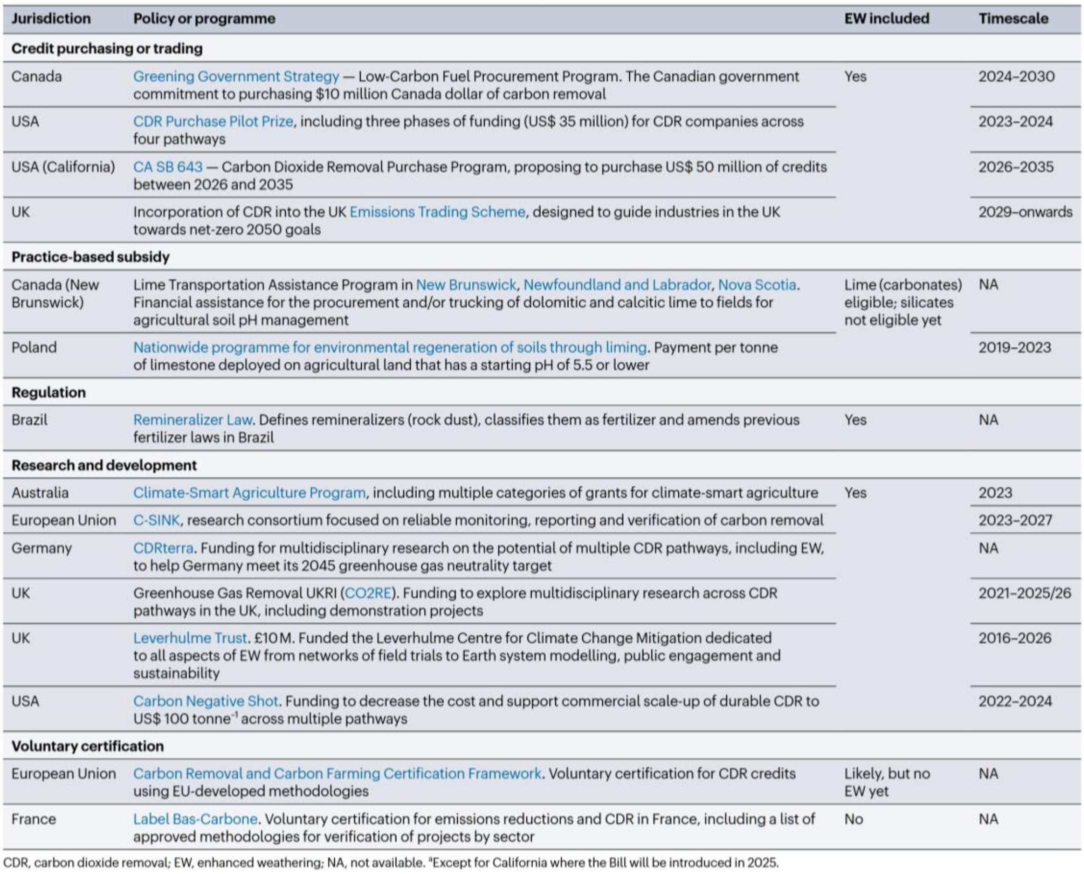
In summary, enhanced rock weathering holds significant promise as a carbon removal tool with ancillary benefits for soil health. Its study relies heavily on mesocosm and pot experiments that provide controlled insights but fall short of capturing the full complexity of field environments (Swoboda et al., 2022; Vienne et al., 2023). Also, one prominent issue that has been highlighted in recent literature (Schiedung et al., 2026) and in stakeholder engagement from this report, was the availability of suitable rock types in sufficient amount to undertake ERW at scale. The absence of extensive, long-term field studies constrains definitive conclusions about large-scale deployment. The science remains dynamic, with increasing but still nascent empirical evidence related to effects on crops, the soil system, socio-economic factors and movement of bicarbonates across the land-ocean continuum, among others (Schiedung et al. 2026); necessitating caution and more research to unravel ERW's full potential and challenges.

4.2.3. Policy and regulation landscape

The current policy landscape regarding enhanced rock weathering (ERW) is characterized by a strong reliance on voluntary carbon markets and private sector initiatives, rather than formal regulatory frameworks (Dörpmund, 2025). At present, the deployment and scaling of ERW are mainly supported through voluntary carbon credits bought predominantly by private organizations. Major firms like Microsoft account for a significant share of ERW carbon credit purchases, contributing around 75% of documented transactions in novel CDR projects, which also include direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS) (CDR.fyi, 2025). The voluntary carbon market (VCM) has expanded dramatically, growing from 5 million credits in 2007 to over 286 million credits in 2023, with a market value exceeding $4 billion in 2024 and projected to expand rapidly (Delacote et al., 2024). This market is vital to funding early-stage and innovative CDR approaches like ERW, which have yet to be incorporated into stricter compliance carbon markets due to the nascent stage of standards and methodologies.

However, the voluntary nature of this market poses challenges, including potential market fragmentation, the need for rigorous verification standards to avoid carbon credit overestimation, and limited public sector involvement (Delacote et al. 2024). Public financing remains limited, and purely private financing may fall short of supporting necessary R&D and deployment at the scale required globally. Some coalitions and climate and development funders are beginning to collaborate to broaden financial support, particularly for programs that integrate carbon removal with agricultural productivity improvements in the Global South.

In summary, while ERW is emerging as a promising CDR solution with growing private sector backing through voluntary carbon markets, the policy environment is still evolving with critical needs for standardized measurement, regulatory frameworks, and public-private partnerships to fully unlock its potential as a scalable climate mitigation technology (Table 6).



Jurisdiction	Policy or programme	EW included	Timescale
Credit purchasing or trading			
Canada	Greening Government Strategy — Low-Carbon Fuel Procurement Program. The Canadian government commitment to purchasing $10 million Canada dollar of carbon removal	Yes	2024–2030
USA	CDR Purchase Pilot Prize, including three phases of funding (US$ 35 million) for CDR companies across four pathways		2023–2024
USA (California)	CA SB 643 — Carbon Dioxide Removal Purchase Program, proposing to purchase US$ 50 million of credits between 2026 and 2035		2026–2035
UK	Incorporation of CDR into the UK Emissions Trading Scheme, designed to guide industries in the UK towards net-zero 2050 goals		2029–onwards
Practice-based subsidy			
Canada (New Brunswick)	Lime Transportation Assistance Program in New Brunswick, Newfoundland and Labrador, Nova Scotia. Financial assistance for the procurement and/or trucking of dolomitic and calcitic lime to fields for agricultural soil pH management	Lime (carbonates) eligible; silicates not eligible yet	NA
Poland	Nationwide programme for environmental regeneration of soils through liming. Payment per tonne of limestone deployed on agricultural land that has a starting pH of 5.5 or lower		2019–2023
Regulation			
Brazil	Remineralizer Law. Defines remineralizers (rock dust), classifies them as fertilizer and amends previous fertilizer laws in Brazil	Yes	NA
Research and development			
Australia	Climate-Smart Agriculture Program, including multiple categories of grants for climate-smart agriculture	Yes	2023
European Union	C-SINK, research consortium focused on reliable monitoring, reporting and verification of carbon removal		2023–2027
Germany	CDRterra. Funding for multidisciplinary research on the potential of multiple CDR pathways, including EW, to help Germany meet its 2045 greenhouse gas neutrality target		NA
UK	Greenhouse Gas Removal UKRI (CO2RE). Funding to explore multidisciplinary research across CDR pathways in the UK, including demonstration projects		2021–2025/26
UK	Leverhulme Trust. £10M. Funded the Leverhulme Centre for Climate Change Mitigation dedicated to all aspects of EW from networks of field trials to Earth system modelling, public engagement and sustainability		2016–2026
USA	Carbon Negative Shot. Funding to decrease the cost and support commercial scale-up of durable CDR to US$ 100 tonne^{-1} across multiple pathways		2022–2024
Voluntary certification			
European Union	Carbon Removal and Carbon Farming Certification Framework. Voluntary certification for CDR credits using EU-developed methodologies	Likely, but no EW yet	NA
France	Label Bas-Carbone. Voluntary certification for emissions reductions and CDR in France, including a list of approved methodologies for verification of projects by sector	No	NA

CDR, carbon dioxide removal; EW, enhanced weathering; NA, not available. [a]Except for California where the Bill will be introduced in 2025.

Table 6: Current status of CDR policies and programmes with respect to ERW across the world (reproduced from Beerling et al. 2025)

4.3. Future Roadmaps for scalability

Enhanced rock weathering (ERW) is a promising carbon dioxide removal (CDR) technique that accelerates the natural rock weathering process by spreading finely crushed silicate rocks such as basalt on agricultural lands. This accelerates the chemical reactions that draw down atmospheric CO_2 by converting it to stable carbonates (or bicarbonates), which are eventually washed into soils, rivers, and oceans for long-term storage. The method also offers co-benefits for soil health and agricultural productivity, making it an attractive climate solution with scalability potential. Currently, researchers point to the involvement of private organizations in governing CDR (Battersby et al., 2022; Dörpmund, 2025). They emphasize on examining the perspective (both preferences and motivations) of such private entities, which is necessary to form appropriate political supervision and responsibly scale-up technologies such as ERW (Reinhard et al., 2023).

- Technology and Infrastructure Utilization

ERW leverages natural geological processes and common materials (e.g., basalt quarry rock), which reduces the need for new, complex infrastructure. Existing mining, crushing, and transport technology can be adapted for ERW, facilitating relatively straightforward scale-up on a broad geographic scale, particularly in countries with extensive croplands like the U.S., China, India, and Brazil. The scalability is further supported by the widespread availability of suitable rock, and agricultural lands where application can be integrated with existing soil amendment practices (Baek et al., 2023; Beerling et al., 2025, 2018).

- Research, Monitoring, and Verification

A critical element for ERW scalability is the development of precise, cost-effective monitoring and verification systems to measure the carbon sequestration rates accurately. There is ongoing research to understand reaction rates of different rock types, the movement and final fate of weathering products, and how environmental factors such as climate and soil chemistry influence effectiveness. Satellite-based technologies and AI tools, such as those deployed by startups for farm-level monitoring, are expected to enable large-scale, real-time tracking and impact assessment, which is crucial for gaining regulatory approval and carbon credit certification (Abdalqadir et al., 2024; Bijma et al., 2026; Schenuit et al., 2025).

- Environmental and Site Suitability Considerations

To scale ERW sustainably, projects must carefully select sites to avoid environmental risks such as CO_2 release from soil drying or acidification from inappropriate fertilizer use. Long-term studies are needed to confirm the permanence of carbon storage and to mitigate potential negative impacts such as particle transport by wind or water. Site-specific adaptations based on soil type, local climate, and agricultural practices will enhance both carbon capture and soil health benefits, addressing uncertainties around ecosystem responses (Levy et al. 2024; Dupla et al. 2025).

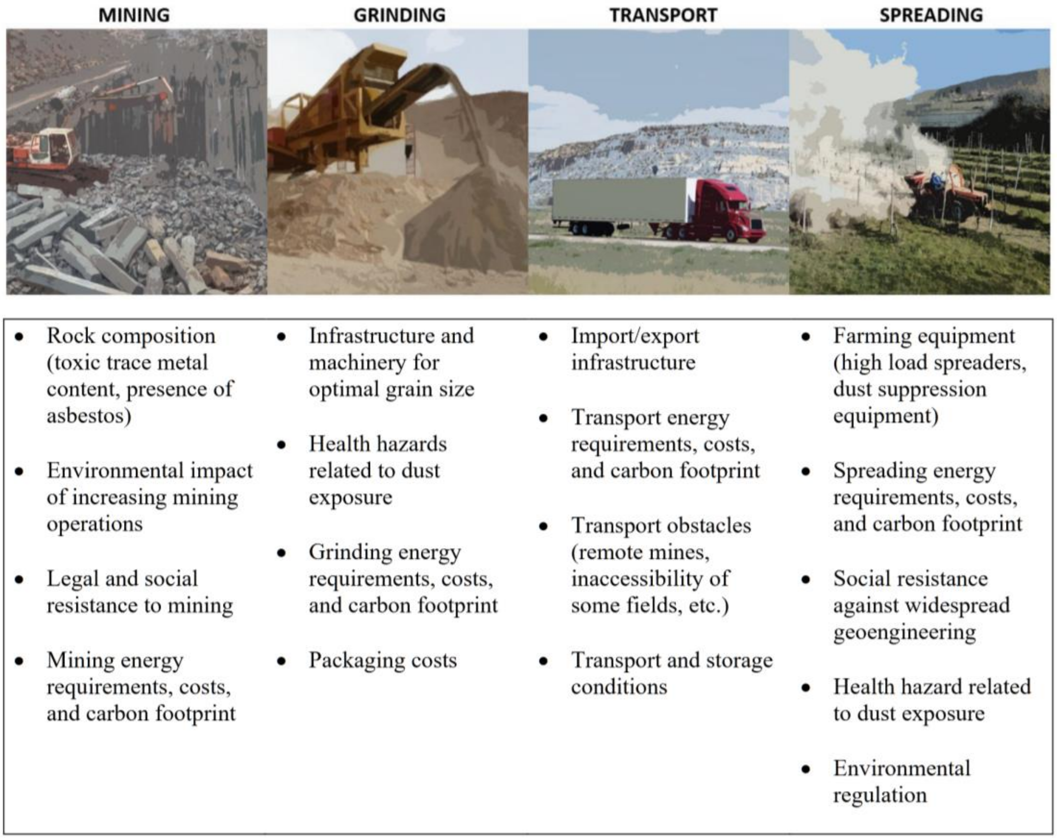
- Economic and Policy Incentives

For widespread adoption, the ERW roadmap includes building economic incentives, including carbon credits and income for farmers through enhanced yields and soil health benefits. Some companies are already investing in ERW projects by purchasing future carbon credits, indicating a growing market interest. Integrating ERW into climate policies, carbon markets, and agricultural subsidy programs will further incentivize large-scale deployment and innovation (Johnstone et al., 2025).

- Future Projections and Challenges

Studies project that extensive deployment of ERW on agricultural lands in major emitter countries could sequester significant amounts of CO_2. However, ERW is currently at a pilot or early commercial stage and not yet ready for huge scale deployment due to uncertainties in effectiveness, measurement challenges, and costs. Continued research, scaling pilot projects, and developing robust environmental guidelines are focal points for moving ERW from promising experimental to mainstream solution(Brad and Schneider, 2023; Schenuit et al., 2025).

In summary, the future scalability of enhanced rock weathering relies on leveraging existing industrial infrastructure, advancing monitoring technology, ensuring environmental safety through careful site selection, and building economic incentives (Fig. 4.6). With these components in place, ERW holds strong potential as an effective, durable, and nature-based carbon removal strategy capable of gigaton-scale CO_2 sequestration while supporting agricultural resilience (Beerling et al. 2025).



MINING	GRINDING	TRANSPORT	SPREADING
• Rock composition (toxic trace metal content, presence of asbestos) • Environmental impact of increasing mining operations • Legal and social resistance to mining • Mining energy requirements, costs, and carbon footprint	• Infrastructure and machinery for optimal grain size • Health hazards related to dust exposure • Grinding energy requirements, costs, and carbon footprint • Packaging costs	• Import/export infrastructure • Transport energy requirements, costs, and carbon footprint • Transport obstacles (remote mines, inaccessibility of some fields, etc.) • Transport and storage conditions	• Farming equipment (high load spreaders, dust suppression equipment) • Spreading energy requirements, costs, and carbon footprint • Social resistance against widespread geoengineering • Health hazard related to dust exposure • Environmental regulation

Fig. 4.6: Diagram showing the different possible limiting factors to scaling ERW on a large-scale (reproduced from Dupla et al. 2025)

CHAPTER 5 - ENVIRONMENTAL AND SOCIAL IMPACT REPORT

5.1 Assessment of environmental impacts of ERW

This section explores the social and environmental impacts from ERW both at a local and regional scale. Although, current literature is lacking on the large scale and long-term impacts of ERW, many studies have used observations of analogous processes (such as the use of other powdered material in agricultural soils) to understand the long-term effects of using rock powder on soil health and its effects on biota.

5.1.1. Impact on soil health

Enhanced rock weathering (ERW), which involves adding silicate rock powder to soils, has notable impacts on soil health that depend on application rate, grain size, and local soil conditions (Levy et al., 2024). The introduction of these minerals can alter soil porosity, moisture retention, and partial pressure of CO_2 within the soil profile, causing complex changes that evolve over time as the rock minerals weather and interact with existing soil constituents. Studies show that the main factor that controlled the effect of the use of rock powders on soil health mainly depended on the mineralogy of the rock powders used. Although, mafic and ultramafic rocks supplied the highest amount of nutrients, even felsic rocks can enrich soils with elements such as K, Ca, Fe^{2+}, etc. (Swoboda et al. 2022). Crushed rocks can also lead to an increase in P content of the soil due to desorption of P caused by competing Si ions (Swoboda et al. 2022). But an excess supply of elements such as potassium (K) can also lead to an imbalance in the concentration of other nutrients, resulting in the decrease of elements such as Ca, Mg, Zn and P in soils (Priyono and Gilkes, 2008). Some studies also indicate that use of rock fertilizers such as basalt, can diminish the amount of nitrous dioxide (N_2O) from crops possibly due to the increase in soil pH (Blanc-Betes et al., 2021).

ERW is associated with a liming effect, since it uses mostly alkaline rocks which stabilizes soil pH by supplying base cations to the soil; this can mitigate soil acidification (Fig. 5.1) common in intensively farmed areas and improve the availability of key nutrients such as calcium, potassium, and phosphorus for crops (Beerling et al. 2025). Studies have shown crops grown in basalt-amended (and other silicates) soils demonstrate higher nutrient concentrations and improved yields, as well as better resilience to environmental stress (Beerling et al., 2024, 2018; Haque et al., 2025; Skov et al., 2024). Similar studies (primary field trials) in India's diverse agro-climatic zones are absent, which has been identified as a key gap in the literature and an important limitation to generalising the findings locally.

In terms of soil biology, studies show contradictory results. Some research shows an increase in parameters such as soil sucrase, catalase enzymatic activity and also alkaline phosphate and urease (when used along with compost) (Li and Dong, 2013). Studies like (Mersi et al., 1992) and (Li et al., 2021) indicate that microbial activity generally increases with silicate rock powder application. While some studies indicate an overall increase in the community-level physiological profiling of the soil (Li et al., 2021), others reported no such change (Ramezanian et al., 2013). But broadly, there appears to be an agreement that depending on the type of silicate mineral used microbial activities increase, with the type of mineral deciding on the type of bacteria that is attracted into the soil (Carson et al., 2009; P. C. Bennett, 2001; Uroz et al., 2015).

When powders with silt or clay-sized grains are applied, soil hydraulic conductivity often decreases, potentially reducing water infiltration. Such fine fractions can oversaturate the pore water space, promoting increased surface runoff, especially under heavy rainfall conditions (Amann and Hartmann, 2019). These hydrological shifts not only affect soil moisture distribution but can impact nutrient absorption and the activity of soil microorganisms vital for plant health. However, impacts may vary as the movement of rock grains and rates of weathering are influenced by climate, water balance, and soil type. There is risk of surface and groundwater pollution if runoff transports excess fine material or leaches contaminants underground. Overall, ERW offers significant co-benefits for soil health and productivity if carefully managed, but continued research is needed into long-term effects on trace element accumulation in soil, nutrient supply, organic matter changes, hydraulic conductivity and pH of freshwater bodies among others (Swoboda et al. 2022; Levy et al. 2024).

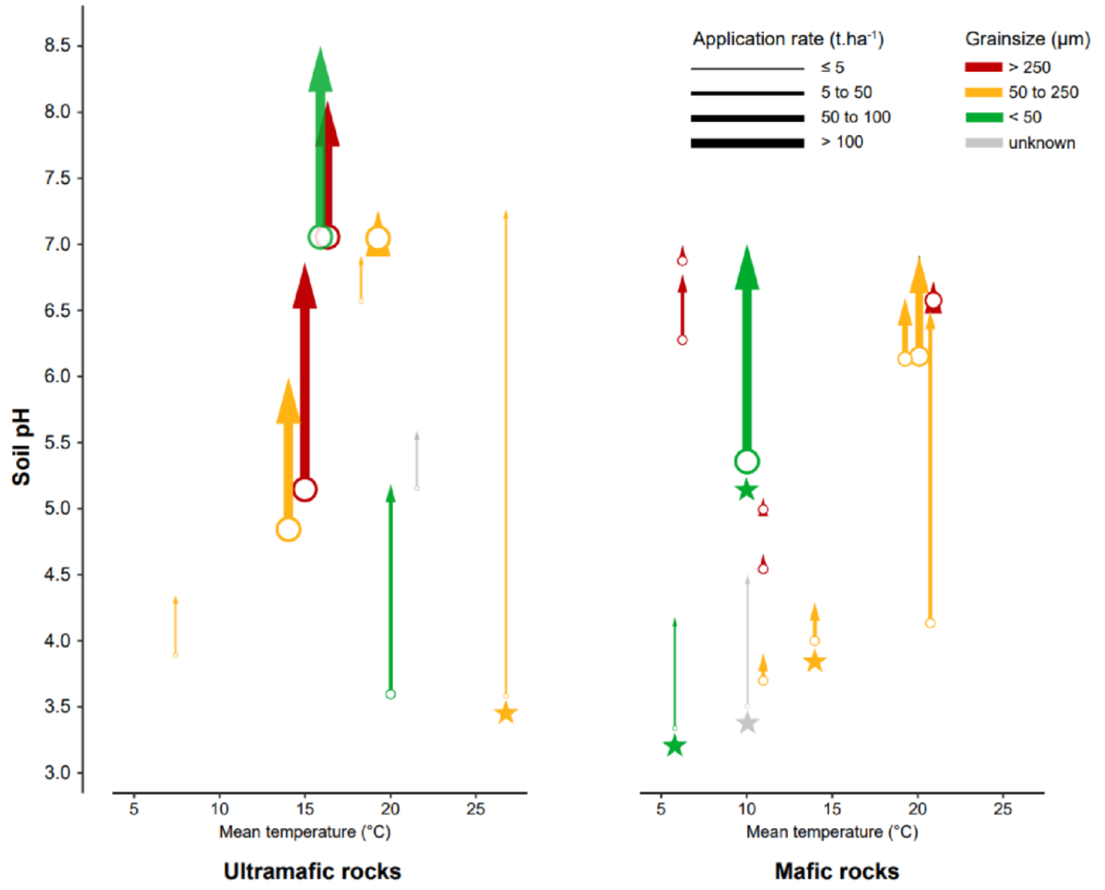


Fig. 5.1: Soil pH changes in ERW mesocosm and field experiments using ultramafic or mafic rocks over a median duration of 12 months. Each arrow represents an experiment, indicating rock powder grain size (p80, (in µm)), application rate (t ha^{-1}), and mean temperature (°C). Field experiments are marked by a star at the base of each arrow (reproduced from Dupla et al. 2025; see Dupla et al. 2025 for reference to the original studies).

5.1.2. Impact on crop health and yields

Enhanced rock weathering (ERW) has demonstrated an overall 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 (Fig. 5.2) (Beerling et al., 2024). These minerals are vital for healthy plant metabolism, hormone regulation, and stress response mechanisms, particularly in soils degraded by intensive farming (Beerling et al. 2018). Most studies showing significant improvement in crop yields has been reported from acidic soils, mainly oxisols (Swoboda et al. 2022). Those from temperate soils generally have used rocks that contain minerals with high dissolution rates (like nepheline).

Additionally, the release of silicon through rock weathering is known to bolster plants' resistance to abiotic stresses such as wind, heat, salinity, and drought. Silicon uptake strengthens plant tissue, making crops less susceptible to physical damage and improving tolerance to adverse conditions (Epstein, 2009). There is also evidence that supplemental silicon in soil can limit the uptake of toxic heavy metals, including cadmium, arsenic, and lead, thereby contributing to safer, cleaner food production (Guntzer et al., 2012). Both experimental and field studies indicate that the amount of bioaccumulation of trace elements in plants is low even if it is high in soils (Beerling et al., 2024; Vienne et al., 2022). Though it must be noted that research on both movement of PTE’s and other trace elements through soil and bioaccumulation, needs more research.

Results from field trials have shown both positive and neutral results with the application of basalt rock dust on crop yields (Fig. 5.2). Studies that showed an increase in crop yield have reported yield increase in the range ~7% - 77% (e.g., 28-77% for maize in Ghana, (Oppong Danso et al., 2025); 9.3-20.5% for spring oat in NE England, (Skov et al., 2024); ~7±4.3% for corn in China, (Guo et al., 2023)), together with improved soil pH and nutrient uptake. On the contrary, some studies have reported no significant change in crop yield (e.g., wheat in Sweden, (Ramezanian et al., 2013); potato in Belgium, (Vienne et al., 2022)). 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 (Dieleman and Janssens, 2011; Rijnders et al., 2024). Crops grown in ERW-treated soils have exhibited higher concentrations of calcium, potassium, and other key nutrients, resulting in improved growth rates and resilience under changing climate and soil conditions. The residual effect of mineral amendments also means enhanced nutrient availability persists over multiple growing seasons, and reducing reliance on synthetic fertilizers (Conceição et al., 2022). Similar studies (primary field trials) in India’s diverse agro-climatic zones remain very scarce, which has been identified as a key gap in the literature and an important limitation to generalising the findings globally.

Studies suggest that most mafic and ultramafic rocks are capable of improving yields, while that may not always be true for K-feldspar/quartz-rich rocks (Ramos et al., 2020; Swoboda et al., 2022). A recent review by Swoboda et al. (2022) suggests, that almost all forms of rock powders show some kind of agronomic benefits and can equalise in terms of effectiveness to commercial fertilizers to a large degree.

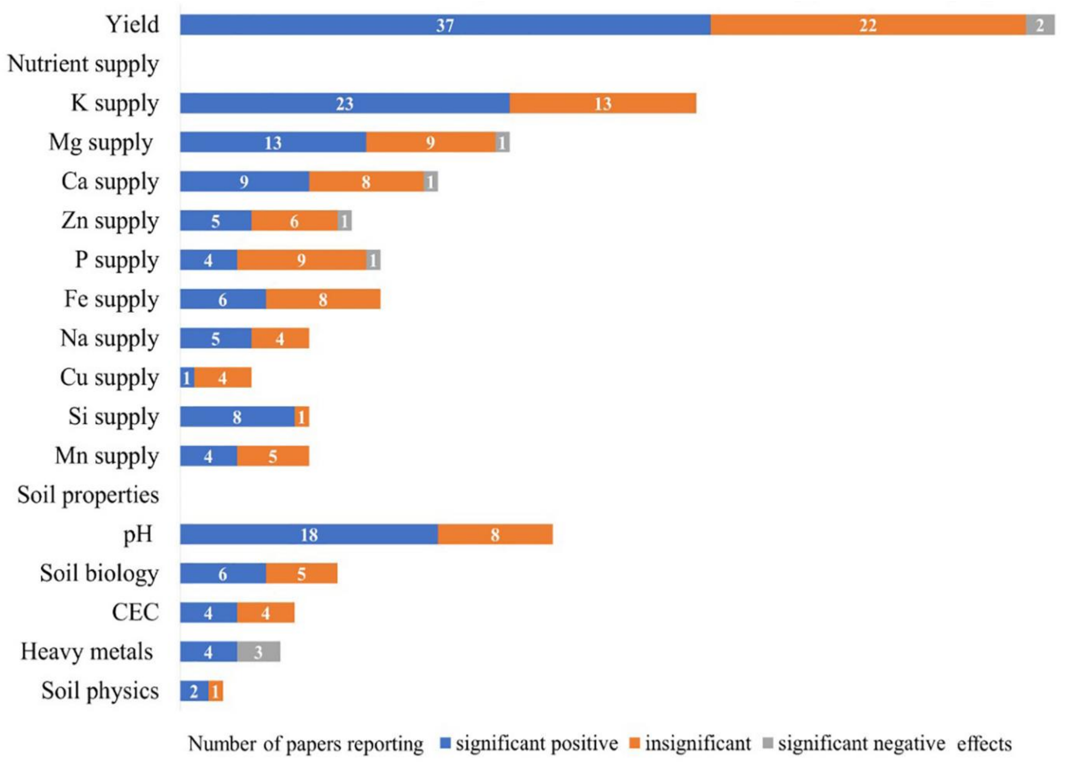


Fig. 5.2: Summary of the effect from 40 studies on crop yield, nutrient supply and soil properties as compiled by Swoboda et al. 2022 (reproduced from Swoboda et al. 2022).

5.1.3. Impact on water bodies

ERW projects focusing on CDR, work on the assumption that bicarbonate ions formed due to weathering eventually migrate into the oceans either via runoff or result in the formation of pedogenic carbonates (Beerling et al., 2025; Haque et al., 2019; Manning, 2025). Some estimates suggest that every year 4.08 x 10^{12} mol of CO_2 is released into the oceans due to natural weathering of terrestrial rocks (Dessert et al., 2003). But any carbonate or elements leached will also enter freshwater streams, rivers, lakes, etc (Table 5). Therefore, the impact of ERW on water bodies maybe understood in terms of their effects on freshwater and marine waterbodies.

FRESHWATER: Studies show that inland waterbodies have undergone widespread acidification post industrialization (Raymond and Hamilton, 2018; Stets et al., 2014). Hence, the inferred alkalization of waterbodies due to ERW maybe considered as a positive effect in some areas (Levy et al. 2024). The effect of ERW on freshwater bodies maybe due to the increase in alkalinity, potential to lower dissolved organic carbon (Levy et al., 2024;

Weatherley, 1988; Yao et al., 2025), or erosion and leaching of trace elements (Amann et al., 2020; Levy et al., 2024).

The primary productivity of phytoplankton is known to be inhibited due to increasing alkalinity and limitations of inorganic carbon (Hein, 1997). Studies indicate that these changes may lead to decrease in photosynthesis (Hasler et al., 2016; Low-Décarie et al., 2015). In contrast, it leads to improvement in the production of carbonate shells in freshwater crustaceans (Ramaekers et al., 2023), modify the food-chain structure (Hasler et al. 2016), cause more nutrient rich phyto- and zooplankton (Hasler et al., 2016; Katkov and Fussmann, 2023; Urabe et al., 2003) and alter the biological availability of metals (Frohne et al., 2011) and change its speciation and complexation (Cuppett et al., 2006; Tang and Johannesson, 2003). Due to the increased silica flux to water bodies associated with ERW, it has the potential to decrease the effect of N and P runoffs from agricultural fields. The increase in Si:N and Si:P is expected to favour diatoms over problem inducing non-siliceous algae (Beerling et al., 2018). Although, extensive research has been done on the acidification of freshwater bodies, studies on the alkalization of such bodies are far fewer (Hasler et al. 2016).

In addition to effects due to changes in alkalinity and inorganic carbon, ERW can impact freshwater bodies due to potential erosion and leaching of trace elements from the applied rocks to the adjoining water bodies. Similarly, there is a concern regarding the movement of toxic elements into the groundwater as the leached elements migrate downward (Dupla et al., 2023; Haque et al., 2020). Such instances of toxic element leaching have been reported from olivine (Amann et al., 2020; Te Pas et al., 2023). On the contrary, not much leaching has been reported from wollastonite (Haque et al. 2020). Research is divided on the potential of metals in soil of being leached. While some studies have shown an increase in nickel (Ni) concentrations in pore water (Amann et al., 2020; Vienne et al., 2022), others have found little to no evidence (Beerling et al., 2024; Berge et al., 2012; Renforth et al., 2015). Theoretical evaluation of leaching rates of heavy metals in acidic forest soils from ERW indicate upper limits as high as 17% for Ni and as low as 3% for Cr (Tyler, 1978). More research is however needed, to understand how these estimates translate to ERW in croplands (Levy et al. 2024). Furthermore, as different minerals contain different proportion of toxic elements, a comprehensive study of feedstock and their ability to leach needs to be studied further (Haque et al. 2020). Also, contradictory and opposite effects may be caused by different elements released during ERW. For example, while phosphorus is known to promote algal blooms (Schindler, 1977; Wurtsbaugh et al., 2019), silica from ERW may reduce algal blooms by favouring diatoms due to change in Si stoichiometry in the water body (Bach et al., 2019; Beerling et al., 2018). Levy et al. (2024) points to the possibility of an increase in turbidity in the water bodies if fine particles generated during ERW gets eroded and transported to streams and other inland water bodies (Weil and Brady, 2018). This may adversely affect the rate of photosynthesis and survival of the aquatic plant life, with long term effects on aquatic food chains.

Theme	**Summary**	**References**
Background & Chemistry	ERW may mitigate freshwater acidification by increasing alkalinity and reducing proportion of dissolved organic carbon, but can mobilize trace elements.	Levy et al. 2024
Biological Effects	Elevated alkalinity may inhibit phytoplankton productivity, enhance carbonate shell formation, alter food webs, and change metal bioavailability.	Hasler et al. 2016; Urabe et al. 2003
Nutrient & Silica Balance	ERW increases Si:N and Si:P ratios, reducing nutrient runoff effects and favouring diatoms over non-siliceous algae.	Beerling et al. 2018
Leaching Risks	Trace metal leaching varies by mineral; olivine shows higher mobility than wollastonite, with effects dependent on soil chemistry.	Vienne et al. 2022; Beerling et al. 2024
Opposing Elemental Effects	Phosphorus promotes algal blooms, while silica from ERW may reduce them by favouring diatoms.	Beerling et al. 2018; Levy et al. 2024
Physical Impacts	ERW-derived particulates may increase turbidity, reducing photosynthesis and disrupting aquatic ecosystems.	Weil & Brady, 2018

Table 7: Summary of the different effects of ERW on waterbodies

MARINE: Large scale deployment of ERW is expected to impact coastal and open marine systems (Fig. 5.3). This impact would be caused mainly by the downstream effects on ocean carbonate chemistry (Doney et al., 2009), along with higher abundance of silicon and solutes from ERW feedstocks from the upstream segment of the process.

The abundance of carbonate ions and calcium carbonate are expected to elevate in the oceans along the coast with an increase in ERW. Modelling of large-scale ERW suggests that the concentration of aragonite ($CaCO_3$) will increase in surface ocean, especially near river mouths (Fig. 5.3). In many cases, increase in carbonate saturation should benefit marine ecosystems along the coast, but transient extreme saturation of carbonates may also have unintended ecological consequences (Levy et al. 2024).

The effect of solutes other than carbonates are less understood and depends on ERW feedstocks and filtering done upstream. Currently, the effect of upstream filtering and efficiency of element transfer is not well studied (Levy et al. 2024). But, simulation studies on the application of olivine in ocean indicate major impact on phytoplankton due to addition of silicon and iron (Hauck et al., 2016; Köhler et al., 2013). Similar to freshwater bodies, an increase in the abundance of silicon may favour greater diatom occurrence in ocean water (Bach et al., 2019). The applicability of such studies to understand the effects of ERW by extension still needs to be researched. Additionally, the transport or possible filtering of silicon and other macro- and micro-nutrients upstream before reaching the ocean also needs to be studied further (Levy et al. 2024).

Lastly, ERW using basalt can have potentially positive impact on the nitrogen use efficiency (NUE) of crop lands (Beerling et al. 2024). There is a well-established inter-relationship between soil pH and increase in NUE (Adams and Martin, 1984; Pan et al., 2020). Therefore, increased NUE may affect oceans by reducing nutrient fluxes from lands used for ERW (Levy et al. 2024).

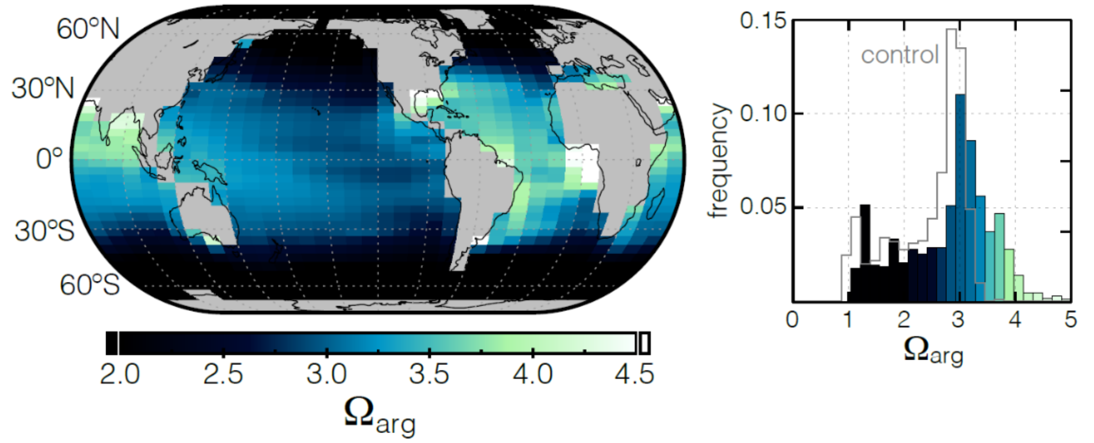


Fig. 5.3: Diagram showing the level of aragonite saturation state (Ω_{arg}) for an Earth system model with intermediate-complexity, assuming a global ERW rate of 10 Gt CO_2 yr^{-1} and moderate human emission pathway (RCP 4.5). Saturation states of aragonite (Ω_{arg}) below 3 is considered to be harmful for calcifying organisms. (Left) Surface aragonite saturation states. (Right) Statistical distribution of (Ω_{arg}) compared to control, where no ERW is assumed (reproduced from Levy et al. 2024)

5.1.4. Impact on air quality

The primary environmental concern on air quality due to ERW comes from rock dusts. Winds can potentially transport rock dust from storage piles or rock sourcing sites to the surrounding areas spreading them on croplands and ecosystems (Levy et al. 2024). Regional scale distribution of dust due to wind is a real possibility; with smaller, drier particles travelling further and in large numbers (Funk et al., 2008). The transport quantity generally decreases exponentially with increasing distance from source (Funk et al., 2008; Tegen and Lacis, 1996). The impact of dust generated during field application and feedstock management on human health is a major concern with respect to ERW. The effect of mineral dust of inorganic composition on human health depends on particle size and composition (Morman and Plumlee, 2013). A study on the effect of basaltic dust in Iceland concluded that they deteriorate air quality which leads to an increase in hospitalization (Arnalds et al., 2016). Studies from marble-processing facilities indicate that fine particulate emissions can also elevate local hospital admissions and respiratory ailments, highlighting the need for proper dust-control measures (Iqbal et al., 2022; Levy et al., 2024). Research by (Schenker, 2000, 2010) and (Schenker et al., 2009) shows that farm workers exposed to silica-rich dust can develop pneumoconiosis and lung inflammation, even in agricultural contexts unrelated to ERW.

The effect of particulate matter on plant health and ecosystems is manifold. If coated by dust particles finer than 10µm, plants show a reduction in photosynthesis and may lead to die-back or death (Farmer, 1993). Observations based on the effect of road dust suggests lichens, liverworts and sphagnum are specially at danger. Experiments on the effect of cement and kiln dust indicate crops are susceptible to the negative effects of dust also (Levy et al. 2024).

5.1.5. Impact on ecosystem

Enhanced rock weathering (ERW) can significantly impact soil ecosystems, largely by altering soil chemistry and biological communities. 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. For example, research demonstrates that these shifts promote soil fertility and structure, thus contributing to improved plant growth and productivity (Desie et al., 2020; Silveira et al., 2021).

Elevated bacterial and earthworm abundance driven by changes in soil pH enhances breaking down organic matter, making nutrients more accessible for plants and other organisms. The proliferation of these soil dwellers—especially earthworms—can accelerate nutrient turnover rates, boost nitrogen mineralization, and generally help sustain the ecosystem's productivity. This transformation is vital in agroecosystems, where nutrient cycling underpins sustainable yields and soil resilience (Levy et al., 2024).

Previous studies, illustrate how ground covering techniques like straw and compost applications can affect belowground invertebrate populations (Thomson and Hoffmann, 2007). By analogy, and corroborated by more recent work (Levy et al. 2024), the addition of rock dust during ERW may similarly shape invertebrate communities in the soil. Since invertebrates contribute to decomposition and nutrient cycling, their response to ERW may have cascading effects throughout the entire ecosystem.

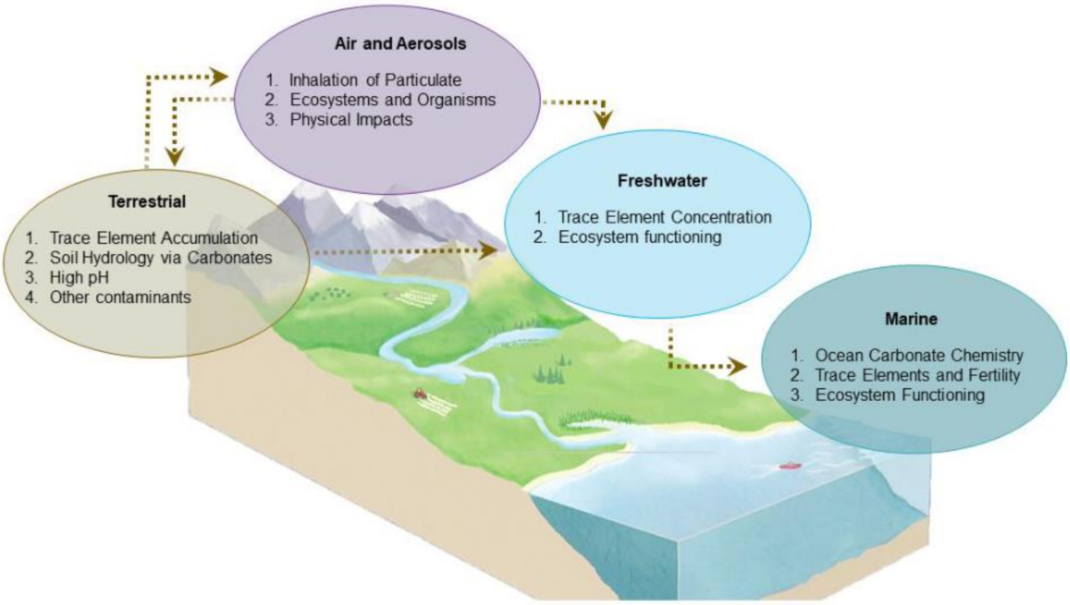


Fig. 5.4: A schematic conceptual diagram showing the different environmental effects of ERW and their interconnections. Arrows indicate the direction of effects that one aspect has on the others (reproduced from Levy et al. 2024).

5.2 Assessment of social impacts of ERW

5.2.1. 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). Since, ERW projects often provide free rock powders for application and it can be applied using existing farm equipment, it is often touted to be beneficial for smallholder farmers, especially in developing countries. But, stakeholder engagement report from this study suggests, that documentation related to land ownership is a common problem associated with such smallholder farmers. Frequently, such farmers lack the proper legal documents related to land ownership, resulting in them being unfairly treated in monetary terms by companies supplying rock dust. Stakeholder views suggests that while millions of dollars are being invested in their name, these smallholder farmers never get the benefit of those funds. This problem is aggravated in areas with tribal and marginalised communities where land ownership may be held collectively, instead of individuals. Studies indicate that inhalation of silica-containing dust from farms may cause pneumoconiosis and lung inflammation in farmers in non-ERW settings itself (Schenker, 2000, 2010; Schenker et al., 2009). Such health hazards typically get enhanced in low-income and disadvantaged regions and countries (Sager, 2020).

Therefore, proper regulatory safeguards need to be in place so that farmers receive the benefit of ERW without being exploited.

In addition to farmers, scaling of ERW is expected to affect miners too. 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. An increase in quarrying, mining and grinding due to higher demand from ERW will increase the exposure of mine workers to silica dust which is known to cause health problems such as pulmonary fibrosis, lung cancer, increased risk of tuberculosis, among others (Davies and Mundalamo, 2010).

5.2.2. Impact on economy

ERW has emerged as a promising carbon dioxide removal (CDR) technique with significant implications for both environmental sustainability and economic growth. 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. An increase in ERW will also increase economic activity in related sectors such as those supplying machinery, tools, legal services, etc. for ERW projects (Oppon et al., 2023). 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 (Beerling et al., 2020; Lefebvre et al., 2019; Smith et al., 2022). The effect of ERW on the economy would vary depending on the country. For example, a country with existing sources of rock powders from mining and other processes will be affected differently compared to one which does not have that amount of source available. For countries that export materials, products and services related to ERW, it will lead not only to economic gains, but also result in environmental damages (Oppon et al. 2023). A recent study based on LCA considerations suggest that resource depletion related to large scale ERW implementation will be highest for countries like India, China, Poland and Germany, while it will be lowest for countries such as Brazil, France, Spain and Canada (Eufrasio et al., 2022). Developed countries are expected to have lesser effect on their environments compared to developing ones due to large scale implementation of ERW (Oppon et al., 2024, 2023).

Policymakers and industries must therefore, ensure that the expansion of ERW practices aligns with sustainable mining standards and low-carbon energy sources. Ultimately, a balanced approach that harmonizes economic opportunity with ecological responsibility will determine the long-term viability of ERW as both a climate solution and an economic driver.

5.2.3. Impact on gender

Our study found no existing literature that examines the effect of ERW specifically, on gender. Considering the technology is still being developed, the absence of studies on the impact of ERW on gender is understandable. The long-term nature of ERW compared to other CDR technologies is also possibly another reason, as the effects of ERW takes at least a few years to be active. 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). 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 (Leal Filho et al., 2023; Patel et al., 2019). Climate change studies have shown that women are more prone to death and injury from extreme climatic events (Alston, 2011; Awiti, 2022). Recent studies suggest that current geoengineering methods like CDR and solar geoengineering tend to put forward masculine values of control, the effects of which are only beginning to be understood (Buck et al., 2014; Sikka, 2018). Globally, climate policymaking has been criticised for not sufficiently accommodating women (Noémi, 2016; Séverine Le Loarne-Lemaire et al. 2021).

In an extensive review, (Pearson et al., 2017) showed that there exists a consistent gap between men and women in how they perceive risks related to the environment. Women generally show more concern compared to men on topics related to climate change and also better perceive risks across different environmental hazards. Additionally, some research suggests that women tend to have more pro-environment and pro-sustainability values compared to men. Also, they tend to transfer these values to others, mainly their children, more (Denton, 2002; Kellstedt et al., 2008). Women in Global South due to their restrictive gender roles and being more susceptible to poverty are less likely to adopt low-carbon and efficient agricultural practices (Carr and Thompson, 2014; Patel et al., 2019). Moreover, due to the lack of literacy and lack of land ownership among women in Global South; they are prevented from adopting different climate mitigation and adaptation practices and from being integrated into new technologies related to agriculture (Hemson and Peek, 2017; Nhamo, 2014). 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 (Fig. 5.5), although the difference is less than 0.14 (on a scale of 1-5).

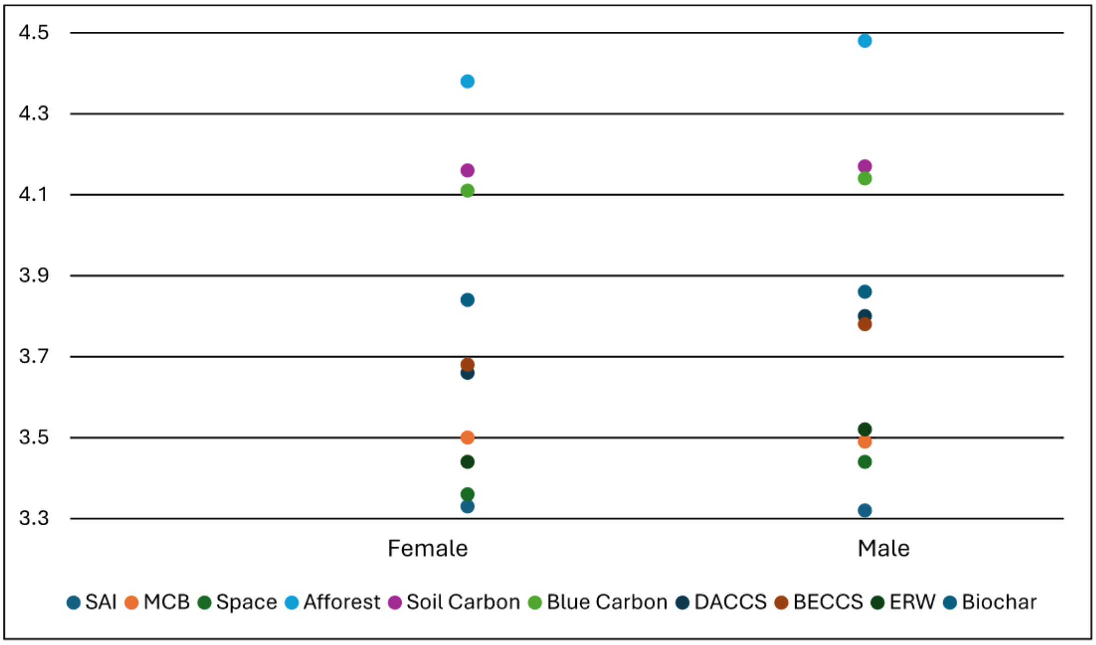


Fig. 5.5: Diagram showing the support for various climate mitigation technologies among women and men (reproduced from Sovacool et al. 2024) [SAI - Stratospheric Aerosol Injection; MCB - Marine Cloud Brightening; Space - Space-based Geoengineering; Afforest - Afforestation and Reforestation; Soil Carbon - Soil Carbon Sequestration; Blue Carbon - Marine Biomass and Blue Carbon; DACCS - Direct Air Capture with Carbon Storage; BECCS - Bioenergy with Carbon Capture and Storage; ERW - Enhanced Rock Weathering; Biochar - Biochar Added to Soil]

CHAPTER 6 – POLICY FRAMEWORK FOR ENHANCED ROCK WEATHERING IN INDIA – THE WAY FORWARD

6.1. Current status of ERW in India

Enhanced Rock Weathering in India is still in its nascent stages, across both public and private sectors. Currently, there are no peer-reviewed studies assessing the effect of ERW in an agricultural setting from India, although, some assessment of ERW feasibility in the Indian context exists (Mir et al., 2023; Pattanaik and Nayak, 2023). But it must be noted, there are studies from India that evaluate the general process of chemical weathering of silicate rocks and its effects on river and groundwater chemistry along with related CO_2 sequestration (Ganvir and Guhey, 2023; Upendra et al., 2025; Vinnarasi, 2020). This review is not aware of any research group in Indian academia, other than one from the National Centre for Earth Science Studies, Trivandrum, who are currently pursuing ERW in an agricultural setting.

In the private sector there are four major companies that are involved in ERW from the country. Their details as gathered from the respective company websites are provided in the table below:

Company	Details	Area of Project	Carbon Credits Sold (source: CDR.fyi)	Carbon Credits Delivered (source: CDR.fyi)
Alt Carbon	Established in 2023, the company is piloting ERW across approximately 300 acres of agricultural land, applying a proprietary mixture of crushed basalt derived from the Rajmahal Traps along with organic inputs across tea, rice and	Darjeeling, West Bengal	21,901 tonnes (as of Jan, 2026)	438 tonnes (as of Jan, 2026)

	bamboo plantations. Company disclosures indicate delivery of 221 tonnes of CO_2 removal to MOL and the issuance of the first credits from the Darjeeling Revival Project on the Isometric Registry. The firm also reports preliminary agronomic improvements, including an average 30% increase in crop yields on treated land. For example, tea yields are reported to have increased from roughly 10 to 20–21 mann (about 400 kg to ~800 kg) per unit area, and rice yields from approximately 50 to 100 mann across five bigha.			
MATI Carbon	Founded in 2022 it has developed an ERW-based model focused on providing mineral soil amendments to smallholder farmers who typically have limited access to conventional fertilizers. The company reports that basalt rock dust has been deployed as an ERW feedstock in rice paddy fields in rural Chhattisgarh, with subsequent expansion across Madhya Pradesh and Jharkhand. Company disclosures state that more than 16,000 smallholder farmers have participated in these deployments, covering over 21,000 acres and involving over 200,000 tonnes of basalt dust application to date. The company also indicates that its operations have delivered over 1,000 tonnes of verified CO_2 removal.	Chhattisgarh, Jharkhand, Madhya Pradesh	13,956 tonnes (as of Jan, 2026)	2,215 tonnes (as of Jan, 2026)

	Mati Carbon further reports that its ERW initiatives extend beyond India, with field trials conducted in Zambia, and additional expansion efforts underway in Tanzania. Mati Carbon is also listed as registered with Puro.earth for CO_2 removal certificates. Additionally, Mati Carbon was named the Grand Prize Winner (USD 50 million) of the XPRIZE Carbon Removal Competition. In an abstract published recently at European Geosciences Union-2025, the team from MATI Carbon reported an increase in crop yield of rice ranging between 14.39-27.79% across Chhattisgarh and Madhya Pradesh (Jordan et al. 2025).			
Varaha	They are implementing ERW projects with smallholder farmers in Madhya Pradesh since its founding in 2022. They report that participating farmers can generate carbon credits through the Puro.Earth standard, providing an additional income stream linked to the adoption of ERW as a land-management practice. The company has announced the issuance of its first ERW credits under the Puro.earth registry, associated with deployments on cotton-growing smallholder farms in Madhya Pradesh. As per these disclosures, Varaha has scaled application to approximately 100,000	Madhya Pradesh	Data Not Available for ERW	Data Not Available for ERW

	tonnes of basalt powder across its project area. The company attributes several co-benefits to these interventions, including improved soil nutrient status, enhanced water-retention capacity, reductions in fertilizer use, and increased crop resilience. The team from Varaha recently published an abstract at the American Geophysical Union-2025 where it reported an increase of 16% in cotton production.			
Everest Carbon	It is a U.S.-based ERW project developer founded in 2022. After identifying India as a promising geography for field deployment, the company has initiated pilot-scale activities and reportedly applied more than 300 tonnes of basalt rock dust within the first few months of operation. However, scaling ERW measurement proved significantly more difficult than anticipated. Reliable quantification of carbon removal required extensive soil and water sampling, laboratory analysis, and logistics across multiple locations, resulting in high costs, long turnaround times, and inconsistent data quality. These limitations highlighted a key constraint for commercial-scale ERW projects: the lack of cost-effective, accurate, and scalable MRV systems.	Madhya Pradesh	3 tonnes (as of Jan, 2026)	3 tonnes (as of Jan, 2026)

	Faced with these challenges, Everest Carbon decided to pause its India deployments and withdraw from existing pre-purchase agreements. This case underscores the broader need for robust, affordable MRV innovations if ERW is to scale responsibly in India and globally.			

Table 8: Details of the different companies currently engaged in ERW in India (Data sourced from the respective websites of the companies).

6.2. Potential of ERW in 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 (Beerling et al., 2020; Eufrasio et al., 2022; Strefler et al., 2018). 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 (Beerling et al. 2020). ERW also has possible co-benefits for India’s improved food and soil security.

Beerling et al. (2020) in a recent analysis involving multiple countries, mapped the distribution of basalt source regions and croplands in India (Fig. 6.1 – top panel). Depending on the distance from basalt source regions to croplands, they evaluated the rail distance, costs and CO_2 emissions that maybe associated with the nationwide adoption of ERW in India (Fig. 6.1 – bottom panel). Fig. 6.1 shows that the costs and CO_2 emissions related to ERW is either lowest or reasonable for most parts of India. This shows the potential to scale ERW across majority of India.

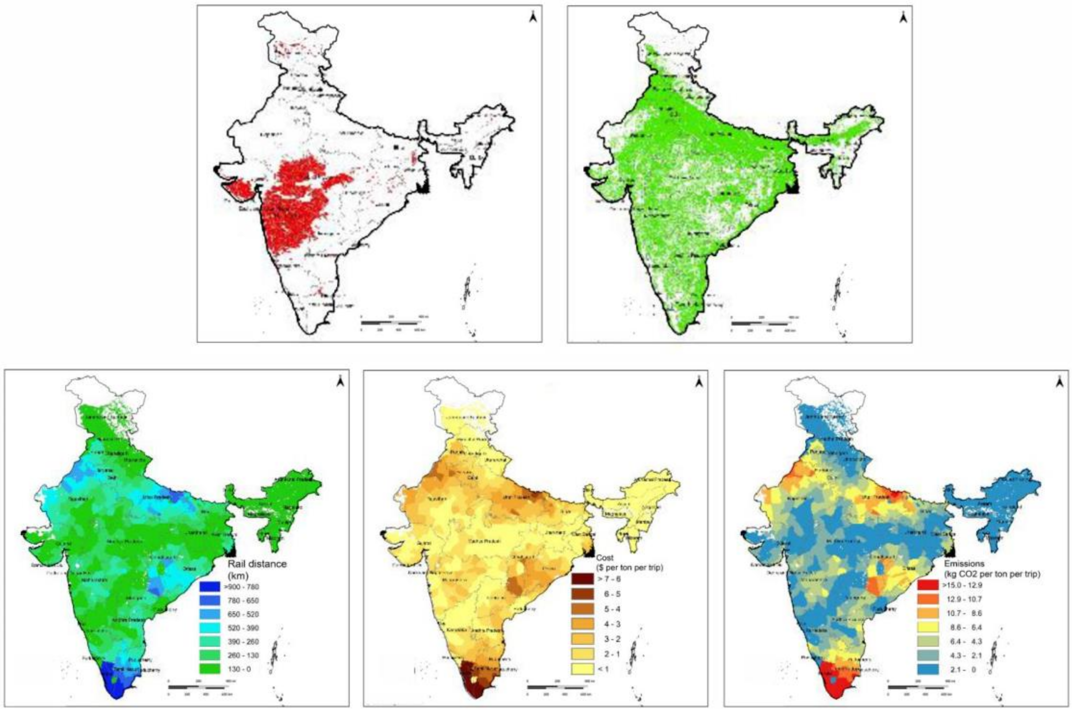


Fig. 6.1: *Top Left* – Map of India showing the location of major basalt source regions. *Top Right* – Map of India showing the distribution of croplands. *Bottom (left to right)* – Map showing the source to cropland rail distances, costs and CO_2 emissions, respectively, for India (modified after Beerling et al. 2020).

Eufrasio et al. (2022) calculated sustainability index of ERW for different countries across the global north and south based on end point effects on resource depletion, ecosystem conditions and human health. Fig. 6.2 shows that India has the second highest potential for scalability and long-term sustenance of ERW in the world. 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. The effect of damage to ecosystems is lower than the effects on resource depletion. It is important to note, that India in this study shows the most vulnerability in terms of impact to human health. Therefore, all precautions must be taken to reduce the impact on human health with respect to large scale deployment across India.

Most field studies on the effectiveness of ERW in an agricultural setting present in the literature have been undertaken at temperate climates mainly from countries in the global north. India is divided into 15 agro-climatic zones (Table 9). 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. To achieve this, India should adapt global policy frameworks to its local contexts by supporting pilot studies.

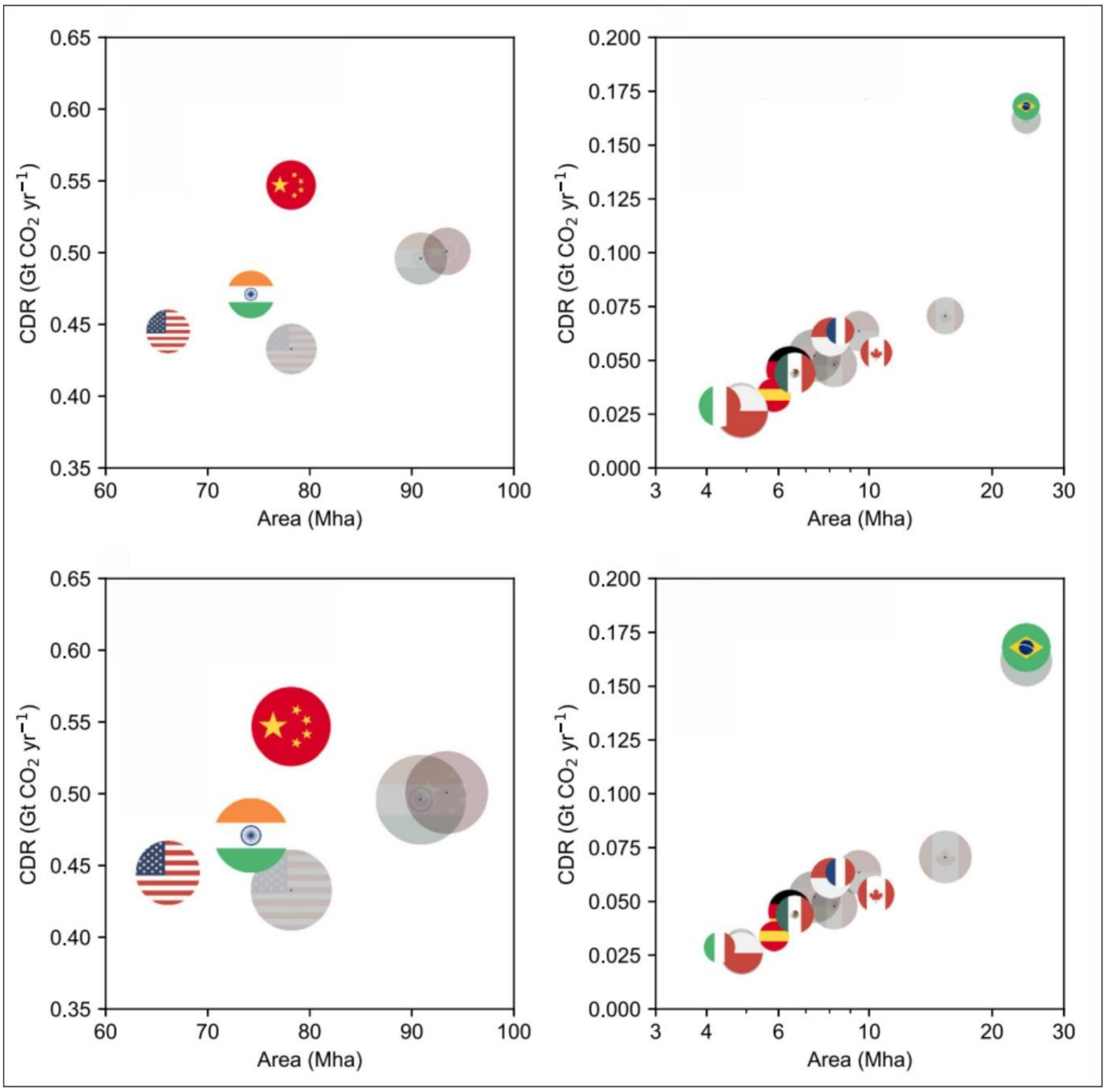
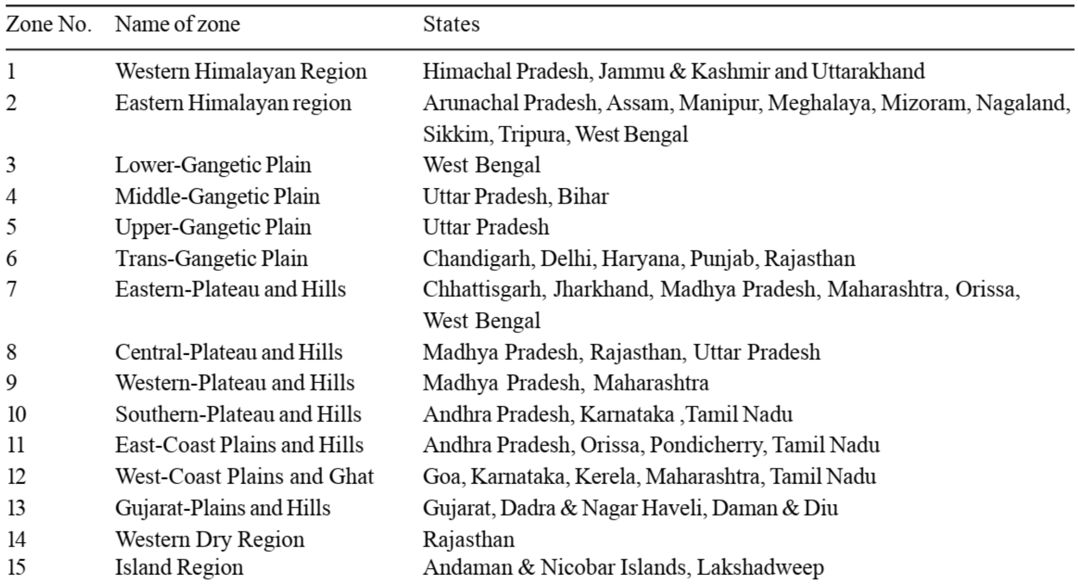


Fig. 6.2: Sustainability and carbon dioxide removal potential of the enhanced rock weathering supply chain across different countries. Sustainability index calculated using the mean of different end point sources (see Eufrasio et al. 2022 for details) relative to cropland under ERW and CDR potential for India, China and USA (top left) and 9 other countries (top right). Bottom panel shows the area integrated sustainability index for the same nations. Bright flags show the results for business-as-usual scenario, while the shaded flag represent results for 2°C energy policy scenarios. Size of circles represent higher index values (modified after Eufrasio et al. 2022).

Researchers recommend involvement of a broad array of stakeholders, including both experts and the public at the early stage of ERW development (Wilsdon & Wills, 2004). They suggest public engagement in a two-way communication to make the public participate in the decision-making process itself from the very beginning of the developmental process (Macnaghten, 2017). Compared to other CDR technologies, trustworthiness of the science, the government and the industry is a crucial factor for garnering public support for ERW. As such, we recommend active involvement of government organisations and departments across all levels of ERW-related R&D, application and farmer awareness.



Zone No.	Name of zone	States
1	Western Himalayan Region	Himachal Pradesh, Jammu & Kashmir and Uttarakhand
2	Eastern Himalayan region	Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, West Bengal
3	Lower-Gangetic Plain	West Bengal
4	Middle-Gangetic Plain	Uttar Pradesh, Bihar
5	Upper-Gangetic Plain	Uttar Pradesh
6	Trans-Gangetic Plain	Chandigarh, Delhi, Haryana, Punjab, Rajasthan
7	Eastern-Plateau and Hills	Chhattisgarh, Jharkhand, Madhya Pradesh, Maharashtra, Orissa, West Bengal
8	Central-Plateau and Hills	Madhya Pradesh, Rajasthan, Uttar Pradesh
9	Western-Plateau and Hills	Madhya Pradesh, Maharashtra
10	Southern-Plateau and Hills	Andhra Pradesh, Karnataka ,Tamil Nadu
11	East-Coast Plains and Hills	Andhra Pradesh, Orissa, Pondicherry, Tamil Nadu
12	West-Coast Plains and Ghat	Goa, Karnataka, Kerela, Maharashtra, Tamil Nadu
13	Gujarat-Plains and Hills	Gujarat, Dadra & Nagar Haveli, Daman & Diu
14	Western Dry Region	Rajasthan
15	Island Region	Andaman & Nicobar Islands, Lakshadweep

Table 9: Table showing the names of different agro-climatic zones of India, along with the respective states and union territories that fall within those zones (reproduced from Rai et al. 2008).

Based on current global practices and policy landscape, this study proposes a set of recommendations as a policy framework for ERW in India. The study takes a cradle to grave approach to provide recommendations with respect to all the life cycle stages of an ERW project.

6.3. Policy Framework

The policy framework has been provided considering a cradle to grave approach for an Enhanced Rock Weathering (ERW) project. The recommendations consider a thorough Life Cycle Assessment (LCA) with respect to emissions and impacts across all ERW stages. For each stage, we identify the relevant activity and provide some general recommendations based on the academic literature and stakeholder engagement. This is followed by a set of regulatory suggestions that should help in the effective management of ERW in that particular stage. The relevant environmental and social safeguards that would help in safely scaling ERW are then discussed, along with the preventive measures that may be mandated for the safe deployment of ERW. Finally, the study proposes appropriate monitoring, reporting and verification (MRV) framework of the various factors affecting ERW along with the respective inspection timelines necessary to effectively monitor each of these stages. The roles of the central, state and local authorities along with those for local communities are also suggested for each stage. Stages 1–4 deal with sourcing of ERW feedstocks till its application whereas, Stage 5 deals with the long-term monitoring of the ERW process to prevent any environmental or social harm. Finally, the report provides some recommendations for building a credible and investable ERW market in India, that not only achieves actual climate change goals, but also strengthens the country's economy. The following sections present indicative recommendations based on the academic literature and stakeholder engagement, and is intended to support informed decision-making.

Stage 1: Upstream Feedstock Sourcing

- ❖ **Activity**: Sourcing of ERW feedstocks

- ➢ **Considerations Informed by Research and Stakeholder Inputs:**
- Naturally occurring silicate rocks and minerals (like basalt, gabbro, wollastonite, olivine, etc.) and artificially created alkaline materials (like steel slag, cement kiln dust, concrete in demolition wastes, etc.), can both be used as ERW feedstocks. There is a dearth in long term field studies related to ERW in general. Moreover, there is a scarcity in academic literature studying the effects of artificially produced

alkaline materials during ERW, compared to those for silicate rocks. Also, there exists a relatively higher degree of risk associated with potentially toxic elements in alkaline materials produced as by-products of industrial processes. Therefore, the present study recommends the use of silicate rocks and minerals for ERW deployment instead of alkaline by-products from industrial processes.

- Ultramafic and mafic rocks (like peridotite, basalt, etc.) are considered the best candidates for ERW due to their high base cation contents compared to felsic rocks such as granite or rhyolite, which increase their carbon sequestration potential. Currently, basalt is the most used rock type for ERW due to its global availability and fast weathering rates. But research shows good potential for olivine-, wollastonite-, nepheline-, mica-, feldspar- and feldspathoid- rich rocks among others. It is important to note that although, ultramafic and mafic rocks (like peridotite, basalt, gabbro, etc.) and minerals (like olivine, pyroxene, etc.) are considered best suited for ERW; use of felsic rocks (like granites, etc.) and minerals (like feldspar, mica, etc.) is also not uncommon for the purpose of improving soil quality and as substitute for artificial fertilizers. Although felsic rocks and minerals are less efficient in terms of their carbon sequestration potential, they may still be used.
- Using ERW feedstocks with similar mineralogy and composition to the soil on which the feedstock is to be applied should be avoided
- The study recommends pursuing systematic and state-of-the-art research on the potential and effects of the different rock types and anthropogenic alkaline by-products as ERW feedstocks, through state-, national- and international-level collaboration between academia and industry.

➢ **Suggested Regulatory Approaches:**

- The study recommends notifying a technical body within the Geological Survey of India (GSI) as the primary advisory and regulatory body for ERW in India. The recommended functions of the body may be:
    - to use the geochemical (National Geochemical Mapping survey) and lithological (Specialised Thematic Mapping project) maps made at a 1:25,000 scale to analyse and select suitable rock types for ERW.
    - to identify and prevent the use of silicate rocks bodies with high concentrations of potentially toxic elements (like nickel-Ni, chromium-Cr,

  zinc -Zn, copper -Cu, arsenic-As, mercury-Hg, cadmium-Cd, etc.) as ERW feedstocks. This is especially significant as ultramafic and mafic rocks (e.g., peridotite) and minerals (e.g., olivine) are often rich in toxic elements such as Ni and Cr which over a certain concentration is known to be harmful to the environment and human health, but environmentally safe in low enough concentrations
  - to identify and prevent the use of rocks with high amounts of sulphides, as those have potential implications for arsenic speciation and contamination
  - to identify and prevent the use of rocks containing asbestiform minerals from the serpentine (e.g., chrysotile) and amphibole (e.g., crocidolite) group of minerals, along with those having significant concentration of radioactive elements (e.g., high U/Th concentration)
  - to determine the maximum extractable limits for the different lithologies; provide technical supervision on the ecological fate of minerals within and beyond the site of application
  - to frame the protocols for measurement, reporting and verification (MRV) relevant to ERW and ensure compliance with them
- The rocks used as ERW feedstocks may be considered for classification using the following nomenclature: igneous rocks (Le Maitre and International Union of Geological Sciences, 2005); metamorphic rocks (Fettes et al., 2007); sedimentary rocks (Boggs, Jr., 2009).
- In light of global best practices and the current state of ERW science, opening new mines purely to supply ERW feedstock is difficult to justify at this stage. The lifecycle emissions from fresh extraction and the ecological disruption involved often undermine the very rationale for ERW. India produces large volumes of quarry waste, mine overburden, and crusher by-products that currently sit unused. These materials should be the first source for any ERW project. ERW feedstocks may be sourced from existing rock quarries. However, focus must be to utilise the already available wastes from construction sector, mine tailings, overburden and mine by-products for current ERW projects. In this regard, the Directorate General of Mine Safety (DGMS), in conjunction with the Geological Survey of India (GSI), may consider identifying mine tailings, overburden and by-products that may be used

for ERW feedstock with proper geochemical characterisation and reclassify them as 'ERW feedstocks'

- Mines and quarries that undergo an extension to provide ERW feedstocks should have to reapply for clearances regarding Environmental Impact Assessment (EIA) and mining leases among others. EIA should ensure no harm is brought on existing biodiversity and sensitive ecosystems as that defeats the purpose of climate change mitigation
- The Central Government may consider prioritizing the notification of permissible upper limits in soil for various potentially toxic elements (such as Ni, Cr, Zn, Cu, As, Hg, Cd, etc.) under the National Mission for Sustainable Agriculture (NMSA), as this could serve as an important step for ensuring environmental and agricultural safety. In this context, the Indian Council of Agricultural Research (ICAR) and State Agricultural Universities (SAUs), in consultation with the Geological Survey of India (GSI) and the Central Ground Water Board (CGWB), may be well placed to guide and support this process
    - The process for determining the national limits should consider avoid using the 'pseudo-total' approach using the *aqua regia* digestion method (e.g., International Organization for Standardization, 1995; US Environmental Protection Agency, 1996)
    - Methods that lead to complete extraction of toxic elements from primary and secondary minerals should be preferred
    - Additionally, such limits could be set for different soil pH and soil types considering the different agro-climatic zones across India
- Since the minerals used for ERW generally fall under the broad category of 'minor minerals', State Governments may be well placed to frame rules for the grant of concessions, determination of royalty rates, and pricing under Section 15 of the Mines and Minerals (Development and Regulation) Act, 1957 (MMDR Act). For certain strategic minerals with alternative use and higher commercial value such as wollastonite and olivine, state's Department of Geology and Mining (or equivalent authority) may set and revise the prices or royalties, through public notifications or tender processes. The study recommends that the average sale price (ASP) of such minerals be reviewed every quarter, benchmarked on local availability and abundance, and average global price (on per tonne basis).

- **Indicative Risk Mitigation Measures:**

- *Potentially Toxic Elements:*
  - Common PTE’s present in mafic and ultramafic rocks such as Ni, Cr, Cu, Zn, etc. are known to have low mobility and as such less likely to contaminate water bodies. But their immobility leads to an increase in their concentration within soil profiles with time and raises the risk of subsequent bioaccumulation. Also, the mobility of PTE’s depend on a large number of factors; and their leaching into water bodies and possible accumulation in soil profiles and within crops has not yet been studied extensively in an ERW setting.
  - Considering the current state of research, it is strongly recommended—perhaps most critically—that silicate rocks or alkaline materials of anthropogenic origin with high concentrations of potentially toxic elements (such as Ni, Cr, Pb, As, etc.) be avoided for ERW.
- *Worker & Employee Safety:*
  - It is strongly recommended that personnel working with ERW feedstocks be provided with appropriate Personal Protective Equipment (PPE) to ensure their safety: – Eye protection (safety glasses), respiratory protection (N95 respirators), hand protection (safety gloves), foot protection (safety boots), hearing protection (ear plugs and muffs), head protection (hard hats or helmets) and body protection (safety vests and suites)
  - It may be beneficial to consider arranging routine health check-ups for personnel working with ERW feedstocks, particularly focusing on respiratory health and hearing, to support their overall well-being and enable early identification of potential issues.
  - It may be worthwhile to consider providing regular safety training for workers and employees, along with ensuring access to timely emergency medical care and hospitalisation in the event of trauma or accidents, in order to enhance preparedness and worker and employee safety.
- *Land Rehabilitation:*
  - It may be appropriate to encourage existing quarries supplying ERW feedstocks to undertake land rehabilitation measures, such as progressive backfilling and afforestation, as part of efforts to restore ecological balance over time.

  - It may be useful to clarify that the applicable rules of the Compensatory Afforestation Fund Management and Planning Authority (CAMPA), along with relevant local mining cesses, would continue to apply in this context, ensuring alignment with existing regulatory frameworks.
  - It may be advisable to consider the establishment of an escrow mechanism by the ERW company, rather than the local mining operator, to support afforestation activities and ensure dedicated allocation of resources
- *Dust Control:*
  - It may be particularly important to consider encouraging the use of covered storage for crushed materials, as this can play a significant role in reducing environmental exposure and supporting safer handling practices
  - It may be beneficial to consider the use of water sprays on benches and stockpiles of ERW feedstocks, as this will help in controlling dust emissions and improving overall site conditions
  - It may be important to consider monitoring dust and other emissions from machinery used during this stage, with appropriate measures to keep them under control and maintain acceptable environmental standards.
  - It may be prudent to consider measures to prevent erosion of ERW feedstocks, as maintaining their stability is important for both operational efficiency and environmental protection

➢ **Proposed Monitoring, Reporting, and Verification (MRV) Framework:**

- For MRV of ERW feedstocks, the wt% of oxides and calculation of the base cation content of the feedstocks may be determined by XRF or ICP-MS or ICP-OES (higher resolution chemical analyses preferred)
- It may be advisable to consider conducting ICP-MS analysis to assess the concentrations of potentially toxic elements, such as Ni, Cr, Cu, As, Hg, and Pb, to better understand and manage any associated environmental and health risks.
- The chemical composition of the mineral phases present in the rock may either be determined semi-quantitatively (mineral end members) using XRD or quantitatively using EPMA. Depending on the mineralogy and chemistry of the rock, dissolution rates may be determined for different ERW feedstocks
- Additional tests to determine the pH of abrasion, amount of free silica and granulometry of the feedstock should also be pursued

- It may be recommended that the designated authority undertake these studies for each batch of ERW feedstock and ensure they are repeated prior to deployment by the organization or individual managing the ERW project. The analyses could be conducted by the ERW project developer through recognized institutions, such as the IITs, CSIR laboratories, or State Universities, with the resulting data made publicly accessible to promote transparency and informed decision-making.
- It may be recommended that the designated authority compare the values reported by the ERW project developer during the pre-deployment phase with those in its own database before granting permission for the use of the analysed rock as ERW feedstocks, to ensure consistency and reliability of the data.
- It may be beneficial to involve the Central and State Ground Water Boards, along with other relevant bodies responsible for surface and groundwater quality monitoring, in assessing the environmental effects of ERW. Their role could include studying potential impacts on groundwater contamination and recharge, as well as monitoring the health of local water bodies, streams, and rivers, to support informed management and safeguard water resources.
- It may be advisable to consider accounting for the additional carbon footprint associated with drilling and blasting, as well as changes arising from Land Use and Land Cover (LULC), if mining activity at an existing site increases beyond a defined threshold (e.g., more than 25%) due to sourcing of ERW feedstock. This could help in understanding and managing the broader environmental impacts.
- *Suggested Inspection*:
    - It may be recommended to consider conducting inspections twice a year by geological, environmental, and mining authorities to verify compliance. In particular, a pre-monsoon visit could focus on ensuring that appropriate safeguards are in place to prevent erosion of ERW feedstocks and any potential leaching of material.
    - It may be advisable to consider granting organisations involved in the MRV process, such as GSI, CGWB, ICAR, and similar bodies, the legal authority to pause or halt a project if potential risks to the environment or society are identified, to ensure precautionary measures can be effectively implemented.

- **Suggested tools and references:** Until guidelines regarding permissible limits on the amount of PTE's in ERW feedstocks emerge nationally, practitioners may consider using the following international guideline as a precautionary measure:

- Brazil, MAPA – Normative Instructions No.5: Published by The Minister Of State For Agriculture, Livestock And Supply (Government of Brazil) regarding the chemical and physical characteristics of materials that may be used as 'Remineralisers' as a substitute or in addition to fertilisers
- Cascade Climate Heavy Metal Accumulation Calculator: The heavy metal calculator developed by the Cascade Climate Foundation can also be used to estimate the amount of heavy metal that may accumulate in the soil

Stage 2: Feedstock Processing and Conditioning

- Activity: Convert quarried rock into fine powder to maximize reaction surface area

- **Considerations Informed by Research and Stakeholder Inputs:**

- The crushing and grinding of ERW feedstocks into fine powders may be undertaken either at the source (i.e., in the mines/quarry) or at the site of deployment (i.e., in and around ERW field site), each having their own advantages and disadvantages. For example, while comminution at field site reduces the environmental hazards associated with transportation of rock dusts, it increases the risk of air pollution at the field site. Either of the approaches may be pursued with adequate environmental safeguards
- The actual size to which the feedstock needs to be grinded for effective weathering involves balancing between - increase in rate of weathering due to finer particle size, increase in energy input costs and carbon emissions involved in crushing and grinding rock powders, and possible detrimental effects on soil porosity, soil structure, etc. due to addition of fine rock dusts.
- Literature suggests mixing of some organic compounds with rock dusts can further enhance the rate of weathering. For example, enzymes belonging to the group carbonic anhydrases (CA) has been shown to increase the rate of silicate dissolution in alkaline soils. The study recommends exploring the use of organic compounds along with rock dusts for increased ERW efficacy

- **Suggested Regulatory Approaches:**
- It would be prudent to consider making Environmental Impact Assessment (EIA) clearance mandatory for rock crushing operations, to ensure that potential environmental effects are properly evaluated and managed.
- It may be advisable to consider ensuring that crushing and grinding operations for ERW obtain the necessary “Consent to Establish” and “Consent to Operate” approvals under the Air (Prevention and Control of Pollution) Act, 1981, and the Water (Prevention and Control of Pollution) Act, 1974, from the relevant State Pollution Control Boards (SPCB), to align operations with established environmental regulations.
- It may be recommended to consider ensuring that workers and employees engaged in rock crushing and grinding facilities are adequately protected in accordance with the Factories Act, 1948, and other relevant labour laws, to safeguard occupational health and safety.
- It may be advisable to consider that any use of organic additives with rock dust be thoroughly tested and certified by recognized institutions, such as the Indian Council of Agricultural Research (ICAR) and the Council of Scientific and Industrial Research-Indian Institute of Chemical Biology (CSIR-IICB), to ensure safety and efficacy.

- **Indicative Risk Mitigation Measures:**
- *Dust Management:*
  - It may be particularly important to consider taking all feasible measures to suppress and manage fine dust particles generated during the crushing and grinding of ERW feedstocks, as these can pose significant health risks.
  - It may be advisable to consider the use of water sprays during and after comminution as a standard practice, to help manage dust generation and reduce associated health and environmental risks.
  - It may be beneficial to consider the use of enclosed crushers, particularly for larger-scale operations, as a measure to help control dust and improve workplace safety.

    - Consider implementing a dry air extraction system, either using a typical pulse jet bag filter or a cyclonic separation method, to help control dust and maintain safer operational conditions
    - Keeping rock powders in closed containers until use is recommended, as this can help minimize dust release and maintain safer handling conditions.
- *Worker & Employee safety:*
    - Personnel should be provided with appropriate Personal Protective Equipment (PPE), including eye protection (safety glasses), respiratory protection (N95 respirators), hand protection (safety gloves), foot protection (safety boots), hearing protection (ear plugs or muffs), head protection (hard hats or helmets), and body protection (safety vests or suits), to ensure comprehensive occupational safety.
    - It may be beneficial to consider arranging routine health check-ups for personnel working with ERW feedstocks, particularly focusing on respiratory health and hearing, to support their overall well-being and enable early identification of potential issues.
    - It may be worthwhile to consider providing regular safety training for workers and employees, along with ensuring access to timely emergency medical care and hospitalisation in the event of trauma or accidents, in order to enhance preparedness and worker and employee safety.
- *Contaminant Testing:*
    - It may be advisable to test batches after crushing and grinding for potentially toxic elements (PTEs) such as Ni, Cr, Pb, Cd, As, and other harmful substances. Batches with elevated PTE levels could be rejected and managed through safe disposal practices to protect health and the environment.
    - Conducting quarterly analyses of the crushed product until deployment is recommended, to ensure that contaminant levels remain below safe thresholds and to support ongoing environmental and health safety.
    - Monthly monitoring of surrounding soil profiles and nearby water bodies is advisable to detect any potential effects from leaching of toxic elements from stored rock dusts, helping to manage environmental risks proactively.

- **Proposed Monitoring, Reporting, and Verification (MRV) Framework:**

- Recording electricity and fuel consumption for grinding and crushing operations is recommended, while giving preference to renewable energy sources where possible, to help minimize life-cycle emissions and reduce environmental impact.
- *Inspections:*
    - It may be recommended to conduct inspections twice a year, on random dates, by geological, environmental, and mining authorities to verify compliance. One of these visits should be scheduled pre-monsoon to specifically assess safeguards against erosion of ERW feedstocks and any potential leaching into groundwater or surrounding soils.
    - Inspections by the State Pollution Control Board (SPCB) on random dates every two months are suggested, to monitor ambient air quality around the facility and ensure ongoing compliance with environmental standards.
    - Random annual workplace safety inspections by labour authorities are recommended, to help ensure that occupational health and safety standards are being maintained.

➢ **Suggested tools and references:** Till government mandated methodologies are proposed for calculation of CO_2 emissions from fossil fuel combustion during crushing and grinding of ERW feedstock, the following tool maybe used:

- United Nations Carbon Offset Platform: The methodology proposed in the United Nations Carbon Offset Platform that calculates project or leakage CO_2 emissions from fossil fuel combustion maybe used for calculating carbon emissions caused by the use of fossil fuels for crushing and grinding of ERW feedstocks

Stage 3: Transportation and Supply Chain Emissions

❖ Activity: Transport crushed rock powder from processing facilities to farmland

➢ **Considerations Informed by Research and Stakeholder Inputs:**

- Stakeholder engagement and most studies on LCA associated with ERW suggests, ~100km to be the distance beyond which ERW might not make sense from a carbon accounting perspective. If the rock is sourced from greater distances, the carbon emission associated with transportation tends to make the LCA of the ERW unfeasible in terms of the net amount of carbon sequestered. But this distance may vary widely depending on the nature of transportation (trucks, trains, etc.), nature of energy source used (fossil emitting/renewable source) for transportation and carbon sequestration potential of the material being transported among others

- India can encourage mobile crushers near farms to reduce haulage of rock powders
- To minimise carbon emissions associated with transportation, the policy framework recommends each ERW project may undertake route optimisation studies to choose optimal routes and mode of transportation
- Vehicles powered by renewable sources should be preferred over vehicles that either use fossil fuels directly (vehicles with internal combustion engine) or indirectly (EV vehicles charged through fossil emitting sources)

➢ **Suggested Regulatory Approaches:**

- Vehicles transporting ERW feedstock are advised to obtain all necessary transport permits and comply with relevant provisions of the Motor Vehicles Act, 1988, including vehicle registration, axle-load, and weight limits, to ensure safe and lawful transportation.
- When transporting ERW feedstock across state borders, it is recommended to comply with all required interstate permits, such as waybills or transit permits, and ensure payment of applicable inter-state GST, to maintain regulatory compliance and smooth operations.
- Vehicles engaged in ERW feedstock transportation should follow the latest emission norms as issued by the Government of India
- If heavy vehicles used for ERW feedstock transportation use rural roads, proper permission must be arranged for, from the Panchayat and District level authorities. Road maintenance agreements should be negotiated between the ERW project developer and the local authorities and communities
- In case, waterways are used for ERW feedstock transportation, adequate permission and coordination is required from irrigation and waterway authorities to avoid blocking canals or rivers and prevent any possible risks from leaching of ERW feedstocks into the waterways

➢ **Indicative Risk Mitigation Measures:**

- *Loading/Unloading Protocol:*
    - Prefer mechanized handling of ERW feedstock for loading and unloading processes

    - If manual labour is used for loading/unloading, ensure PPE and labour law compliance
    - During the loading and unloading process, it is recommended to use a dry air extraction system, either with a typical pulse jet bag filter or a cyclonic separation system. Additionally, at a minimum, the use of water sprays should be ensured to help control dust generation.
- *Dust Control:*
    - It may be beneficial to regulate operations to ensure proper maintenance of access roads and regular water-sprinkling at storage sites, whether at the mine or near the deployment site, to help control dust and maintain safe working conditions.
    - Adequate road watering and wheel-wash stations should be arranged to minimize dust dispersal and maintain safer transport conditions
    - Proper dust covers should be used throughout all stages of the loading and unloading process to help control dust emissions and protect worker health.
- *Dust Suppression on Roads:*
    - In the absence of current rules on transportation of feedstock, ERW transportation needs to align with current standards and procedures mentioned in the provisions under the Fly Ash Notification, 1999 and its subsequent amendments in 2009, 2016, and 2021, issued under the Environment (Protection) Act, 1986.
    - Following the above-mentioned rules ERW feedstocks must be transported only in closed bulkers or covered vehicles (e.g., tarpaulin covers) to prevent dust pollution
    - Mines and users of ERW feedstocks could make monthly data on production and consumption publicly available on their websites. This transparency would support public monitoring, help reduce transport-related inefficiencies, and allow better tracking of dust emissions.
- *Worker & Employee safety:*
    - Provide personnel with proper Personal Protection Equipment (PPE) – Eye protection (safety glasses), respiratory protection (N95 respirators), hand protection (safety gloves), foot protection (safety boots), hearing protection (ear

plugs and muffs), head protection (hard hats or helmets) and body protection (safety vests and suites)

  - Periodic health check-ups for workers and other personnel, focusing on respiratory and hearing health, should be arranged to support early detection of potential issues and promote overall well-being.
  - Providing regular safety training and ensuring access to emergency hospital care in the event of trauma or accidents can help enhance worker preparedness and safety.

- **Proposed Monitoring, Reporting, and Verification (MRV) Framework:**
- Emissions from fossil fuels used in transporting ERW feedstocks should be included in the life-cycle assessment (LCA) to provide a more comprehensive understanding of the project's environmental impact.
- Explore route optimization and use of cleaner vehicles to reduce carbon footprint
- Maintaining digital records, including detailed transport logs and GPS tracking of vehicles carrying ERW feedstocks, can help ensure clear chain-of-custody and support audit and compliance processes.
- *Inspection:*

  Random checks by the SPCB and transport departments, both on-site and during transport, could be conducted to verify dust containment and compliance with load regulations, helping maintain environmental and safety standards.

- **Suggested tools and references:** Till government mandated methodologies are proposed for calculation of CO_2 emissions from fossil fuel combustion during the transportation of the feedstock, the following tools maybe used:
- Gold Standard Tool for Emission from Freight Transport: Tool No. 2 of the 'Methodology Tools' outlined in the Gold Standard provides suggestions on how to account for emissions from freight transportation based on fuel consumption, vehicle type and distance travelled, among others. Until formal guidelines emerge, project developers can use this document as a framework for their own calculations.
- United Nations Carbon Offset Platform: The methodology proposed in the United Nations Carbon Offset Platform that calculates project or leakage CO_2 emissions from fossil fuel combustion maybe used for calculating carbon emissions caused during transportation of ERW feedstocks

Stage 4: Field Application

❖ Activity: Spread rock powder onto croplands

➢ **Considerations Informed by Research and Stakeholder Inputs:**

- Typically, ERW feedstock application on croplands is pursued just before monsoon season for optimal mineral dissolution
- There still exists considerable debate regarding the amount of rock powder to be used for ERW. The amount of applied rock powder can vary from as low as ~1 t ha^{-1} to as high as ~200 t ha^{-1}. The amount of rock dust applied is decided on a variety of factors including the carbon sequestration potential of the applied material, area of land to be covered, CO_2 removal goals, soil properties, etc.
- The amount of ERW feedstock to be used may be decided on a case-by-case basis depending on baseline soil data, geochemistry of the rock, purpose of use (CO_2 removal vs soil quality improvement), etc.
- The degree of tillage depth is also an important factor to be considered for ERW efficiency. The study recommends adhering to the current agricultural practices followed by the farmers in the area to facilitate easier adoption among farmers. Conservation tillage practices (like no-till, strip-till, etc.) can also be pursued with possible implications for improved carbon sequestration potential.
- The study recommends promoting research and application of ERW in barren and waste lands to try and turn them into either agricultural land or managed forests for additional soil benefits and carbon sequestration

➢ **Suggested Regulatory Approaches:**

- Deployment of ERW should be avoided on disputed or sensitive lands and allowed only on sites with clear and documented ownership, to ensure legal compliance and reduce potential conflicts.
- The study recommends establishing written agreements between the involved parties that explicitly states – consent of the land owner, schedule of application, responsibilities of the involved parties, proper clarity on the nature of benefit sharing with respect to crop yields and sale of carbon credits, data-sharing obligations, duration of contract, and dispute resolution clauses among others
- Securing written consent from the land or farm owner through a thorough Free, Prior, and Informed Consent process is crucial. Farmers must fully understand, in

their local language, the potential impacts on soil quality, risks from potentially toxic elements, effects on crop yields, and terms regarding carbon credit sales, making this step essential for responsible and ethical ERW deployment. These contracts need to be translated into local languages and should not rely on literacy for comprehension; audio or video explanations in regional languages should accompany written forms where literacy levels are low.

- The ERW project developer should establish an escrow account with sufficient funds to cover insurance against potential crop failures during the agreement period, as well as any long-term impacts on the agricultural productivity of the land, ensuring financial safeguards for landowners.
- Local governing bodies, such as the Panchayat and District Administration, should be kept informed about the project, with the project developer ensuring that all information is communicated clearly in the local language.
- Coordination with irrigation and watershed authorities should be ensured to prevent any disruption to existing water channels and safeguard local water management systems.

➢ **Indicative Risk Mitigation Measures:**

- *Method of Application:*
  - The study suggests the use of calibrated mechanical spreaders if possible. In case of manual application ensure proper personal protective equipment is provided to the personnel involved in spreading rock dusts
  - ERW feedstocks should be applied under conditions that minimize dust dispersion, such as early morning or late evening hours, or during periods of high humidity, to reduce environmental and health impacts.
  - Accompany ERW feedstock application with water misting to further prevent the spread of dust
  - The spreading of rock dusts using aerial methods, such as planes or drones, should be avoided to prevent uncontrolled dispersion and associated environmental risks.
- *Mitigation measures:*
  - Buffer strips or vegetative barriers should be established along plots where ERW is applied during the first two years, covering at least one monsoon season, to prevent potential runoff. These barriers may be removed once monitoring authorities confirm that the runoff water chemistry is environmentally safe.

    - If monitoring indicates an increase in potentially toxic elements in the soil, bioaccumulation in crops, or adverse changes in soil properties such as pH or nutrient content, the application of ERW should be paused and appropriate corrective measures implemented.
- *Worker & Employee safety:*
    - Personnel should be equipped with appropriate Personal Protective Equipment (PPE), including safety glasses for eye protection, N95 respirators for respiratory safety, gloves for hand protection, safety boots for feet, ear plugs or muffs for hearing, hard hats or helmets for head protection, and safety vests or suits for body protection, to ensure comprehensive occupational safety.
    - Routine health check-ups focusing on respiratory and hearing health should be arranged for personnel involved, supporting early detection of potential issues and overall well-being.
    - Regular safety training should be provided to personnel, along with ensured access to emergency hospital care in the event of trauma or accidents, to strengthen preparedness and protect worker safety.

➢ **Proposed Monitoring, Reporting, and Verification (MRV) Framework:**

- The study recommends that baseline and follow-up soil tests should at least include the following parameters: soil pH, soil organic carbon content, total alkalinity, cation exchange capacity of the soil, soil porosity, soil texture, macro/micronutrients concentration in the soil, amount of dissolved inorganic carbon in soil pore water, concentration of potentially toxic elements in the soil and gas flux measurements between the soil-air system
- Detailed application logs should be maintained, recording GPS coordinates of the farm, date and time of application, rate of application, and the method used for spreading rock dust, to ensure traceability and accountability.
- Control plots should be maintained to ensure data collection and comparison is possible related to onsite accumulation of PTE's, change in soil parameters such as soil pH, soil inorganic and organic carbon concentration in soil and changes in soil texture among others
- Focus must be on increasing efficiency of current farmlands through ERW instead of converting more forests into farmlands. In case forests are converted to farmlands and ERW feedstocks applied to them, ensure carbon accounting considers that

- *Inspections:*
    - Soil and crop tissue should be tested twice a year to monitor for potential accumulation of toxic elements, helping to safeguard both environmental and food safety.
    - The involvement of the ICAR is recommended to monitor soil health and crop yields along with district agriculture officers
    - SPCB officials should conduct annual checks during the application of ERW feedstocks

➢ **Suggested tools and references:** Every effort must be made such that the concentration of potentially toxic elements (PTE's) in the soil does not exceed safe levels. Before such guidelines are mandated regarding the concentration of PTE's in soil, the following reference maybe consulted in the meantime:

- Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health: These guidelines provide a maximum concentration for different organic and inorganic materials in soil, water and air and maybe consulted for choosing areas with suitable soil types. These limits get updated over time and the latest regulations should be consulted.

Stage 5: Long-term Effectiveness and Impact Monitoring

❖ Activity: Develop an integrated standard operating procedure for long-term monitoring, reporting and verification of carbon storage and ensure safeguards work against any possible long-term environmental and social harm

➢ **Considerations Informed by Research and Stakeholder Inputs:**

- There exists considerable gap and debate in the academic literature regarding the MRV processes and long-term effects of ERW. For India, currently there exists no peer-reviewed publicly available data related to ERW in an agricultural setting. Therefore, India should pursue and encourage local long-term studies and other MRV related research to develop a locally relevant MRV framework for ERW
- International ERW protocols mandate contaminant testing, energy-use MRV, and specific geochemical thresholds (e.g., MAPA,2016-Brazil), among others. India

currently lacks ERW-specific rules; projects should adopt current global best practices voluntarily until formal guidelines emerge

- A unified robust MRV framework should be developed across the entire life cycle of the ERW process

➢ **Suggested Regulatory Approaches:**

- The government should establish detailed rules and regulations that define clear environmental and social thresholds, exceeding which an ERW project must be halted and source materials reassessed. Contingency plans should also be prepared to address any potential environmental or social impacts.
- Develop/adapt a national ERW MRV protocol aligned with international standards, specifying sampling depth, frequency, analytical methods, PTE thresholds, uncertainty handling, permanence criteria, additionality tests and leakage assessment, among others. The protocol should also contain instructions regarding data templates, verification protocols, reporting schedules, and assigned oversight responsibilities (involving central, state and local agencies)
- It is recommended that data related to the effectiveness of ERW in crop yields and its effect on the environment (including soil and waterbodies) be studied thoroughly and published in peer-reviewed Q1, Q2 or Q3 (Web of Science/Scopus Index) journals for the first three years of any ERW project. Such studies should aim to provide a complete elemental budget accounting for the amount of major and minor cations and anions involved getting in and out of the complex and open system that is ERW (mass balance approach) and the pathways taken by those ions. This requirement should complement, not replace, the initial and ongoing monitoring conducted by relevant governmental authorities.
- MRV summaries and findings from inspections should be submitted to Panchayat-appointed local committees and the relevant farmers or landowners in their local languages, allowing them to consult academicians for review. These local committees could also serve as the initial stage of a formal grievance-redressal mechanism, enabling farmers and neighbouring communities to raise concerns related to dust emissions, water impacts, and other environmental or social effects.
- Registries that certify carbon credits related to ERW, such as Puro.earth or Isometric, should be engaged to audit data, sampling methods, and carbon calculations, and to generate carbon credits that could be linked to India’s Green

Credit Scheme. Data verified by these registries should be shared and updated every six months on the websites of the relevant notified government body maintaining the data, the ERW companies, and the registries themselves, ensuring transparency and accountability.

- It is strongly recommended to ensure that the generated carbon credits meet the criterions of ‘additionality’ and ‘permanence’. It must also be made sure that there is no double counting of the issued credits and any future leakage is accounted for.
- Clear rules establishing reporting deadlines for the various aspects of MRV should be put in place, to ensure timely submission of data and consistent monitoring of ERW projects.
- Regulations could require the engagement of independent auditors, such as SGS or Earthood, to review ERW projects every two years, covering all five stages of the project to ensure comprehensive oversight and accountability.
- For ERW projects that span multiple administrative areas or impact shared water resources, formal agreements should be established to clearly define monitoring responsibilities and carbon credit allocation, helping to prevent disputes and ensure coordinated management.

➢ **Indicative Risk Mitigation Measures:**

- Quarterly monitoring of water quality is very important to be considered to help ensure early detection of any changes. Regular assessment of nearby streams, irrigation channels, ponds, and groundwater bodies could include parameters such as pH, dissolved ion concentrations, and PTE levels. In addition, tracking potential impacts on aquatic life may provide valuable insights into broader ecological effects.
- Involvement of Central Ground Water Board (CGWB), along with other agencies engaged in watershed management, could be considered for periodic quarterly reviews of downstream impacts. Such coordination may help strengthen oversight and improve understanding of potential effects over time.
- The study recommends that ICAR should do mandatory tests of crops grown under ERW setting right before every harvest season, to check for bioaccumulation in crops and possibly halt harvesting and release of the crops into the market in case of significant bioaccumulation

- SPCB & Agriculture Departments may consider conducting random inspections—quarterly facility audits and field audits

➢ **Proposed Monitoring, Reporting, and Verification (MRV) Framework:**

- MRV protocols may benefit from incorporating parameters across the Near Field Zone (NFZ), Far Field Zone (FFZ), and the Life Cycle (LCA) of ERW deployment. Providing clear definitions for each of these components, along with sufficient flexibility to adjust their scope based on project-specific conditions, could enhance their applicability. For instance, while the depth of the NFZ may be specified, allowing for adjustments in response to variations in soil horizons, tillage practices, and related factors may support more context-sensitive implementation.
- Protocols could take into account relevant counterfactual scenarios, such as potential reductions in fertilizer use associated with ERW application and the natural carbon sequestration capacity of the feedstock. In a similar vein, life-cycle assessments may also incorporate emissions arising from activities such as drilling, blasting, transportation, and field application, among other related processes, to support a more comprehensive evaluation.
- Sampling protocols may establish a minimum sampling density and frequency per unit area to support consistency in monitoring efforts. It may also be useful to ensure that sampling density scales proportionally with increases in application area, rather than following inverse relationships, so as to avoid placing smaller landholders at a relative disadvantage in terms of MRV-related costs.
- Follow-up sampling should incorporate key soil health indicators along with the measurement of PTE concentrations. Including these parameters may help provide a more comprehensive understanding of changes over time and support ongoing evaluation of environmental impacts.
- MRV protocols could place emphasis on maintaining GPS-linked metadata across a range of data types, including application logs, transport records, energy consumption data, and sampling results. Ensuring such geospatial traceability may enhance data integrity and support more transparent verification processes.
- Consideration could also be given to accounting for emissions associated with both cloud-based data storage and local storage systems used for MRV-related information. Including these sources may contribute to a more comprehensive assessment of the overall emissions footprint.

- Weathering models estimating carbon sequestration might benefit from adjustments that account for local climatic conditions, including temperature, rainfall, and evapotranspiration rates. Incorporating these factors could improve the accuracy and relevance of sequestration estimates for specific regions.
- MRV protocols could clarify the specific stage at which carbon is considered removed—whether upon binding in soil minerals or following leaching into groundwater, streams, or oceans. Aligning this approach with international best practices may help ensure consistency and reduce the risk of over-crediting or under-crediting.
- Provisions could be developed to address the management of issued carbon credits in the event of land-use changes on farmland. Establishing clear guidelines may help maintain the integrity of the carbon accounting framework while accommodating shifts in land management.
- Regulations may benefit from clarifying how the downstream transport of dissolved bicarbonates and minerals into waterways is accounted for in carbon credit calculations. Providing guidance on this aspect could help ensure that sequestration is measured consistently and transparently.
- After the initial phase of ERW deployment, such as 5–10 years, it may be advisable to conduct annual assessments to verify the permanence of outcomes and identify any unforeseen effects. Regular monitoring during this period could help sustain the long-term effectiveness of the intervention.
- MRV guidelines could be designed to evolve in line with emerging research, with updates to the protocol considered every two years based on the latest national and international findings. Requiring projects to submit revised MRV plans for review and approval may help ensure that monitoring remains current and scientifically robust.

➢ **Suggested tools and references:** The long-term removal of CO_2 and its MRV should try to abide by the core carbon principles until formal policy is released. To align current ERW projects with the global voluntary carbon market the following tool may be referenced:

- The Integrity Council For The Voluntary Carbon Market: Each ERW project should aim to align itself with the core principles outlined by the Integrity Council that builds up trust and brings transparency to the carbon market where the generated credits are traded, thus, enabling sustainable growth of the economy

FINANCIAL AND REGULATORY LEVERS FOR SCALING ENHANCED ROCK WEATHERING

This section provides some general suggestions on financial and regulatory levers that may be introduced in India on a national level that will help in scaling ERW across India, creating a sustainable green economy in India generating more jobs, achieve actual climate change mitigation goals and make India a global leader in the carbon market. The suggestions are discussed here under:

- Enhanced Rock Weathering could be integrated into India's climate and agricultural policy frameworks, positioning it as a complementary approach within the country's broader Net-Zero strategy. This may help align ERW initiatives with national climate and sustainability goals.
- The study recommends establishing a dedicated task force under the NITI Aayog or, the Ministry of Environment, Forest and Climate Change (MoEFCC) or, the Bureau of Energy Efficiency or any other inter-ministerial body to coordinate among the various organisations (like GSI, ICAR, SPCB, etc.) involved in regulating and managing ERW in India
- Carbon Credit Certificates (CCC) should be issued against carbon dioxide removed during ERW projects and be allowed to be traded following the current Perform Achieve and Trade (PAT) scheme and eventually within the framework of the Carbon Credit Trading Scheme (CCTS)
- The government can consider putting in regulatory frameworks that ensure the carbon credits generated through ERW and other mechanisms meet the criterions of 'additionality' and 'permanence', and are backed by state-of-the-art MRV protocols that are aligned with best practices suggested in the academic literature
- The present study recommends creating a shared research network involving educational and research institutes to undertake regular MRV processes that may be leveraged by small landholder farmers at subsidised rates
- Measures could be introduced to prevent double counting of carbon credits from ERW projects within the National Framework for Indian Carbon Markets, whether

under compliance or voluntary mechanisms. Clear guidance on this may help maintain the credibility and integrity of the carbon credit system.

- Enhanced Rock Weathering could be considered for inclusion within Corporate Social Responsibility (CSR) activities under the Companies Act, 2013. Encouraging its adoption in this context may help mobilize private sector participation in sustainable climate and agricultural initiatives.
- Reporting of carbon dioxide removal through ERW could be incorporated into Business Responsibility & Sustainability Reporting (BRSR) and considered for inclusion within companies' Environmental, Social, and Governance (ESG) frameworks. This may help enhance transparency and encourage corporate engagement in climate-positive practices.
- The government may consider generating corporate demand by setting Science Based Targets for mandatory buying of carbon credits for all publicly listed companies and private firms and PSU's that meet any two of the following three criteria: (i) More than ₹ 250 Cr. annual net turnover (ii) More than ₹ 150 Cr. in net assets (iii) More than 250 employees
- Enhanced Rock Weathering could be incorporated into the National Mission for Sustainable Agriculture, with relevant data integrated into the Soil Health Mission. Such alignment may support more informed soil management practices and strengthen climate-smart agricultural strategies.
- Farmers could be encouraged to adopt ERW feedstocks as an alternative to artificial fertilizers through incentives under the Pradhan Mantri Kisan Samman Nidhi scheme. Additionally, labelling crops produced using these methods as 'Natural' or 'Fertilizer-Free' may help promote sustainable practices and increase consumer awareness.
- Linking ERW adoption to India's existing crop insurance infrastructure offers a practical solution to farmer apprehension to new soil interventions like ERW. Farmers who enrol in certified ERW programmes should be incentivised under the Pradhan Mantri Fasal Bima Yojana.
- Support for ERW procurement and funding could be facilitated through both public banks, such as State Bank of India and National Bank for Agriculture and Rural Development, as well as private institutions like Industrial Credit and Investment Corporation of India and Housing Development Finance Corporation Bank Ltd.

Engaging these financial channels may help expand access to capital for ERW initiatives.

- Public funding could be allocated to support research and development of ERW initiatives through the Department of Science and Technology. Such support may help advance scientific understanding and facilitate the development of effective ERW technologies.
- Most importantly, India must ensure that ERW and other aspects of the green economy grows in harmony with nature, which has been the traditional and indigenous way of development.

ADAPTIVE GOVERNANCE AND PERIODIC REVIEW MECHANISM

The current policy framework takes into account the ever-evolving nature of the science related to enhanced rock weathering. Hence, it recommends setting up of provisions that regularly reviews the policy with respect to the latest scientific findings related to the chemistry of the process, long term environmental effects and studies on the socio-economic impacts of ERW deployment. Therefore, the current study suggests two mechanisms for regular review of the policy with standardised triggers that requires an update in the policy. These are given below:

A. Scheduled Review

- Comprehensive review every 5 years
- Independent scientific advisory panel
- Public reporting requirement
- Parliamentary or ministerial reconsideration mechanism

B. Science-Triggered Emergency Revision Clause

- Provision for immediate policy amendment if:
    - New peer-reviewed findings materially change risk profile
    - Environmental or public health concerns emerge
    - MRV integrity is compromised
- Temporary suspension powers if required

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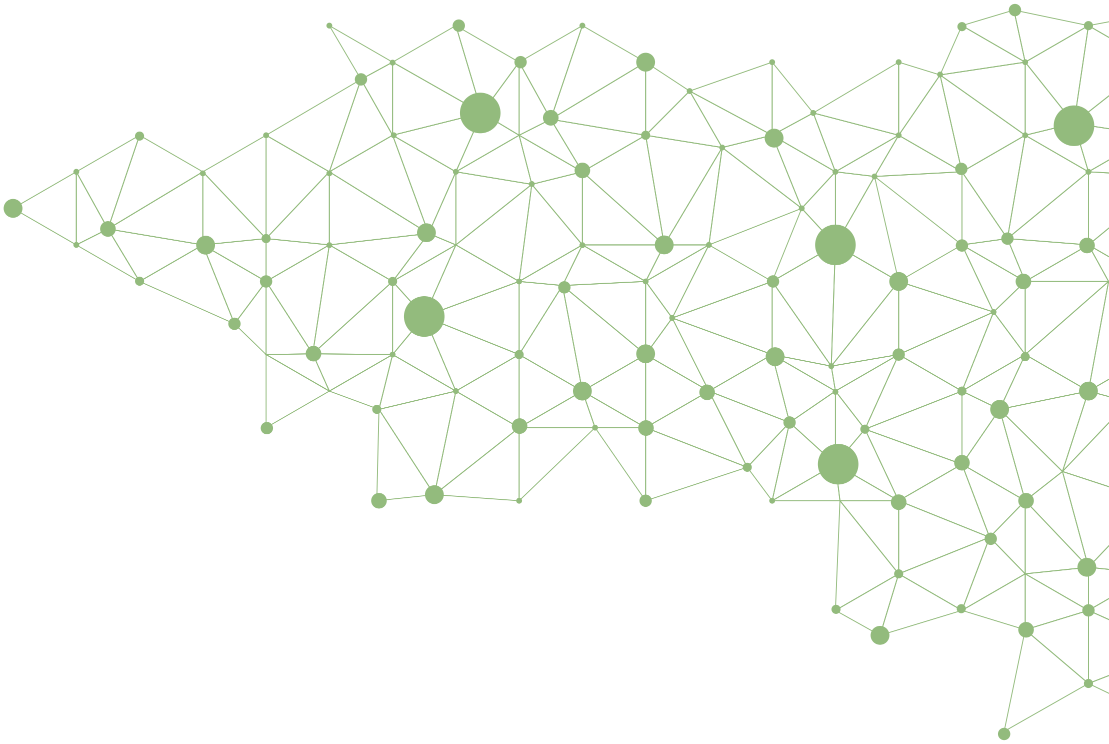

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