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

## Executive Summary

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MANHBUM ANANDA ASHRAM NITYANANDA TRUST · LAULARA
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# 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 21$^{st}$ century. Basalt alone can sequester 230–250 kg $CO_2$ 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, |

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| | nutrient availability (Ca, Mg, K, Si, Fe), and reduces dependence on synthetic fertilisers. |
| **India's Advantage** | 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.

**Manbhum Ananda Ashram Nityananda Trust (MANT)**

+91-8420011313

www.mant.org.in

mant.kolkata@gmail.com