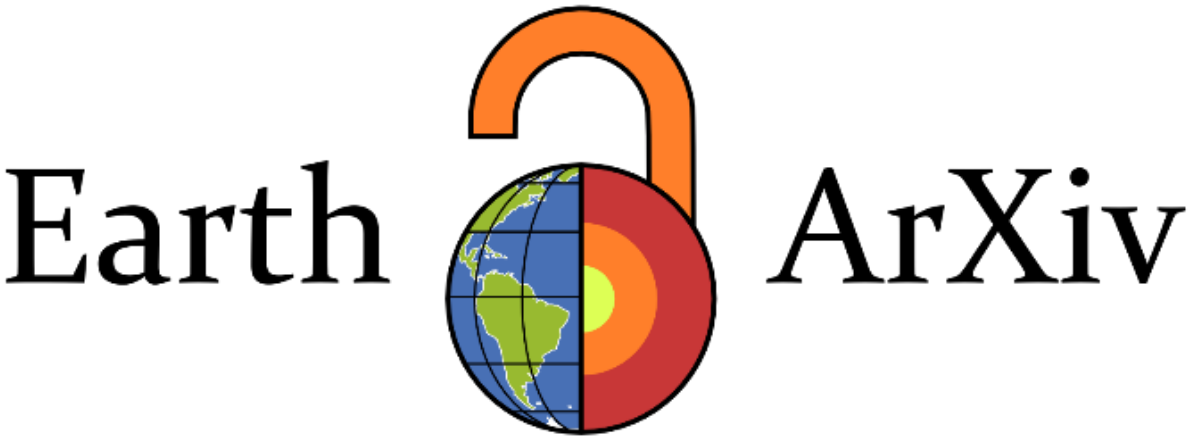

Atmospheric Mineral Carbonation and the Case against $Ca(OH)_2$ Dispersal: A Four-Barrier Feasibility Analysis

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Abstract

Carbon dioxide removal (CDR) technologies are essential for climate stabilization, yet chemical plausibility does not guarantee practical viability. The atmospheric dispersal of $Ca(OH)_2$ exemplifies this gap. While the carbonation reaction is permanent and chemically straightforward, its deployment faces four critical barriers: a carbon-positive production cycle, uncontrollable ecological deposition, aerosol physics constraints and the absence of transboundary governance frameworks. This analysis demonstrates that these barriers represent fundamental domain-specific issues rather than mere technical hurdles. Collectively, they impede responsible deployment. This perspective offers an analytical screening framework for atmospheric intervention proposals, emphasizing that chemical elegance must correspond with ecological safety, governance legitimacy and spatial control before significant research investment occurs.

Introduction

The stability of global environmental systems depends on humanity's capacity to remove gigatons of atmospheric CO_2. To meet the goals of the Paris Agreement, recent assessments indicate a requirement to remove approximately 10 Gt CO_2 per year globally by mid-century [2], with cumulative removal estimates ranging from 100 to 1000 Gt CO_2 over the 21st century [1]. Existing approaches face significant limitations because

biological sequestration remains vulnerable to fire and land-use reversal [3], while direct air capture demands substantial energy inputs and currently operates at a kiloton scale [7]. These constraints motivate the exploration of alternative CDR technologies.

One such proposal involves the aerosolized dispersal of calcium hydroxide [$Ca(OH)_2$] into the atmosphere to facilitate mineral carbonation. This pathway is governed by the following reaction:

$$Ca(OH)_2\ (s) + CO_2\ (g) \rightarrow CaCO_3\ (s) + H_2O\ (l)$$

Stoichiometric calculations suggest this reaction captures 0.594 kg of CO_2 per kilogram of $Ca(OH)_2$ to produce $CaCO_3$. The material requirements are consequently enormous; necessitating approximately 1.68 Gt of $Ca(OH)_2$ per gigaton of CO_2, a scale comparable to current global cement production [4] [5]. This analysis formalizes a four-barrier screening framework to systematically evaluate the structural impediments to atmospheric dispersal, distinguishing these intractable hurdles from more viable CDR alternatives.

However, the conceptual simplicity of this reaction does not translate into real-world viability. Atmospheric dispersal introduces complexities encompassing production-emission challenges, ecological exposure, aerosol physics and transboundary governance issues. These factors intersect to fundamentally alter the feasibility of $Ca(OH)_2$ deployment. This perspective examines why atmospheric $Ca(OH)_2$ dispersal confronts barriers that preclude responsible development and considers the implications for broader CDR screening criteria.

Analytical Framework: The Four Barriers to Deployment

The Production-Emission Paradox

Conventional calcination processes are inherently carbon-positive, with the related cement industry contributing approximately 8% of current global industrial CO_2 emissions [6]. The primary reaction for its synthesis is:

$$CaCO_3\ (s) \rightarrow CaO\ (s) + CO_2\ (g)\ \Delta H = +178\ kJ/mol$$

This process releases approximately 1.0 Gt of CO_2 for every 1.68 Gt of $Ca(OH)_2$ produced, which effectively offsets the theoretical capture potential before accounting for energy, transport and environmental impacts [4]. A comprehensive life-cycle assessment would likely indicate net-positive emissions. Achieving net-negative results necessitates gigaton-scale net-negative production. While pathways like calcination with integrated carbon capture or electrochemical decomposition exist in principle, none operate beyond a pilot scale [7] [8] [9]. Establishing a decarbonized production pathway for gigaton-scale $Ca(OH)_2$ represents a major industrial undertaking requiring substantial capital investment. While decarbonized production is chemically possible, the gigaton-scale infrastructure requirement creates a temporal barrier that likely exceeds the critical window for 1.5°C stabilization. If such capacity existed, would atmospheric dispersal constitute a more optimal use of resources than ocean alkalinity enhancement or enhanced weathering [8] [10]?

Uncontrolled Ecological Consequences

Atmospheric dispersal implies $Ca(OH)_2$ will eventually deposit across terrestrial and marine surfaces. At the gigaton scale, this deposition induces unavoidable biogeochemical disturbances. $Ca(OH)_2$ fundamentally alters soil chemistry because even minor increases in pH can reduce the availability of essential nutrients like phosphorus, iron, manganese and zinc [11]. Soil microbial communities are highly sensitive to pH regulation and undergo significant shifts that impact decomposition rates, nitrogen cycling and plant-microbe symbiosis [12].

Oceanic deposition is equally disruptive to local alkalinity regimes. Research into ocean acidification and alkalinity enhancement demonstrates that shifts in the marine carbonate system can significantly stress calcifying organisms like corals and pteropods [13] [14]. Unlike controlled terrestrial or marine alkalinity enhancements, atmospheric dispersal precludes proactive management. Operators cannot target tolerant ecosystems, adjust dosing based on real-time monitoring or reverse consequences once particles have settled. This lack of spatial control represents a structural risk that distinguishes atmospheric dispersal from more localized CDR methods.

Atmospheric Physics Constraints

Effective CO_2 capture requires $Ca(OH)_2$ to reside in the atmosphere for sufficient periods. Yet aerosol physics imposes strict residence time limitations [15]. Tropospheric dispersal grants particles a lifetime of days to weeks because gravitational settling limits their residence. This rapid removal restricts the carbonation process and concentrates regional deposition. Stratospheric dispersal could extend the lifespan to months or years but necessitates energy-intensive deployment strategies that increase life-cycle emissions [16].

Aerosol behavior varies significantly with particle diameter: small particles (0.1–1 μm) exhibit longer residence times but lower reactive mass, while larger particles (5–20 μm) offer greater surface area but experience rapid settling. Gigaton-scale alkaline injection would also disturb atmospheric chemistry beyond CO_2 capture [17]. Alkaline particles may also act as cloud condensation nuclei and potentially modify cloud microphysics, albedo and regional precipitation patterns [18]. In the stratosphere, heterogeneous surface reactions might influence ozone chemistry, introducing risks analogous to sulfate aerosol injection [19]. These constraints arise from fundamental physical processes rather than industrial or political limitations.

Governance and Transboundary Impact

The concept of atmospheric aerosol dispersal is inherently transboundary. The location of deposition depends on the dispersal point, altitude, seasonal circulation patterns and precipitation [17]. No single nation can deploy aerosols into the atmosphere without potentially imposing environmental risks on others, which contravenes the principle of no transboundary harm codified in international law [20].

At present, no international framework explicitly authorizes irreversible transboundary environmental interventions with asymmetrically distributed harm. Unlike ocean alkalinity enhancement or terrestrial weathering, which can be initiated within national jurisdictions or specific maritime zones, atmospheric dispersal is inherently chaotic and un-targetable. This makes the asymmetry of potential harm uniquely difficult to govern under the "No Harm" principle. Previous governance regimes, such as those addressing acid rain, required decades to develop and

proved effective only where source–receptor relationships were clearly established. These conditions are absent in global aerosol dispersal [21] [22].

Discussion

Advancing $Ca(OH)_2$ carbonation necessitates overcoming all four barriers simultaneously. While no single barrier violates physical laws, their co-existence creates a compounding failure – success requires coordinated breakthroughs in industrial chemistry, atmospheric science, ecology and international law. The structural nature of the aerosol physics and governance barriers suggests a systemic intractability that favors the immediate prioritization of more spatially-controllable CDR alternatives.

The four-barrier framework distinguishes atmospheric dispersal from more tractable CDR alternatives. Ocean alkalinity enhancement (OAE) utilizes identical carbonation chemistry but permits controlled addition, offering continuous monitoring and spatial targeting [8]. Enhanced weathering applies alkaline materials to agricultural soil, combining carbon removal with soil improvement [10]. Concrete carbonation mineralizes CO_2 within existing infrastructure, leveraging established supply chains while avoiding environmental exposure [23].

Implications: Screening Criteria for Atmospheric Interventions

Analysis of $Ca(OH)_2$ deployment reveals four distinct barriers which impede all atmospheric interventions until systematically addressed. Firstly, the production emission paradox: does the approach achieve net-negative emissions under realistic production scenarios? Secondly, the environmental control: can dispersal be targeted, continuously monitored and adjusted based on observed ecological effects? Thirdly, atmospheric predictability: are atmospheric interactions understood to a degree that unintended consequences can be avoided? And finally, governance: do legitimate governance frameworks exist which can govern the transboundary effects of $Ca(OH)_2$ deployment?

Atmospheric $Ca(OH)_2$ dispersal currently fails all four criteria. More broadly, this analysis suggests that approaches requiring uncontrolled atmospheric particulate dispersal demand proportional skepticism, regardless of apparent chemical elegance. These barriers provide a robust basis for

evaluating similar intervention strategies, aiding in the identification of those unlikely to be viable under current technological and governance conditions.

Conclusion

Atmospheric $Ca(OH)_2$ carbonation demonstrates that chemical simplicity is insufficient for climate intervention. The four barriers identified here are structural rather than merely technical – they reflect fundamental constraints in physics, ecology and law. Research prioritization must favor techniques with tractable deployment pathways rather than those requiring uncontrolled atmospheric dispersal. Responsible intervention requires asking whether a deployment is feasible and ethically justifiable within Earth systems, rather than whether the underlying reaction is favorable. Chemical elegance is not enough.

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