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COMMENTARY

Enhanced strategies for carbon dioxide removal using natural minerals

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Carbon Dioxide Removal (CDR) technology plays a crucial role in mitigating climate change and achieving carbon neutrality. One of the promising CDR strategies involves leveraging naturally abundant minerals to capture atmospheric CO_2 and convert it into stable carbonates or dissolved bicarbonates, the process is also defined as enhanced weathering (EW). Silicate minerals are estimated to remove more than 10^5 Gt CO_2 and sequester them as stable and innocuous carbonate minerals or dissolved bicarbonate ions. The carbonization process of these minerals closely mimics natural geological phenomena, which makes it environmentally friendly and minimizes its ecological impact. Furthermore, the mining and processing costs of these minerals are relatively low, estimated at 0.6-1.2 MWh/t CO_2 captured. This stands in stark contrast to other carbon capture technologies, such as direct air capture, which can cost up to 1.8–2.7 MWh/t CO_2 captured. This cost efficiency offers a supreme economic advantage for large-scale implementation. Additionally, the by-products of the mineral carbonization process can be repurposed in industries like construction, where they can be used as building materials, adding further economic value. In the meantime, the foundation for mineral carbonization is well-established, and its scalability makes it an attractive option for widespread deployment. However, the practical implementation of this method is hindered by a critical scientific challenge: the inherently slow reaction rates under natural environmental conditions, which significantly limit its efficiency and scalability.[1] Accelerating this reaction kinetic is therefore a key research priority, as it is essential for unlocking the full potential of mineral carbonation as a viable and scalable CDR solution. Here, from the perspective of reaction principles, we reviewed typical methods for accelerating the mineralization rate and compared their effectiveness and associated risks. Generally, the key to enhancing the reaction rate lies in how to transform low-reactivity natural minerals into highly reactive substances through specific methods.

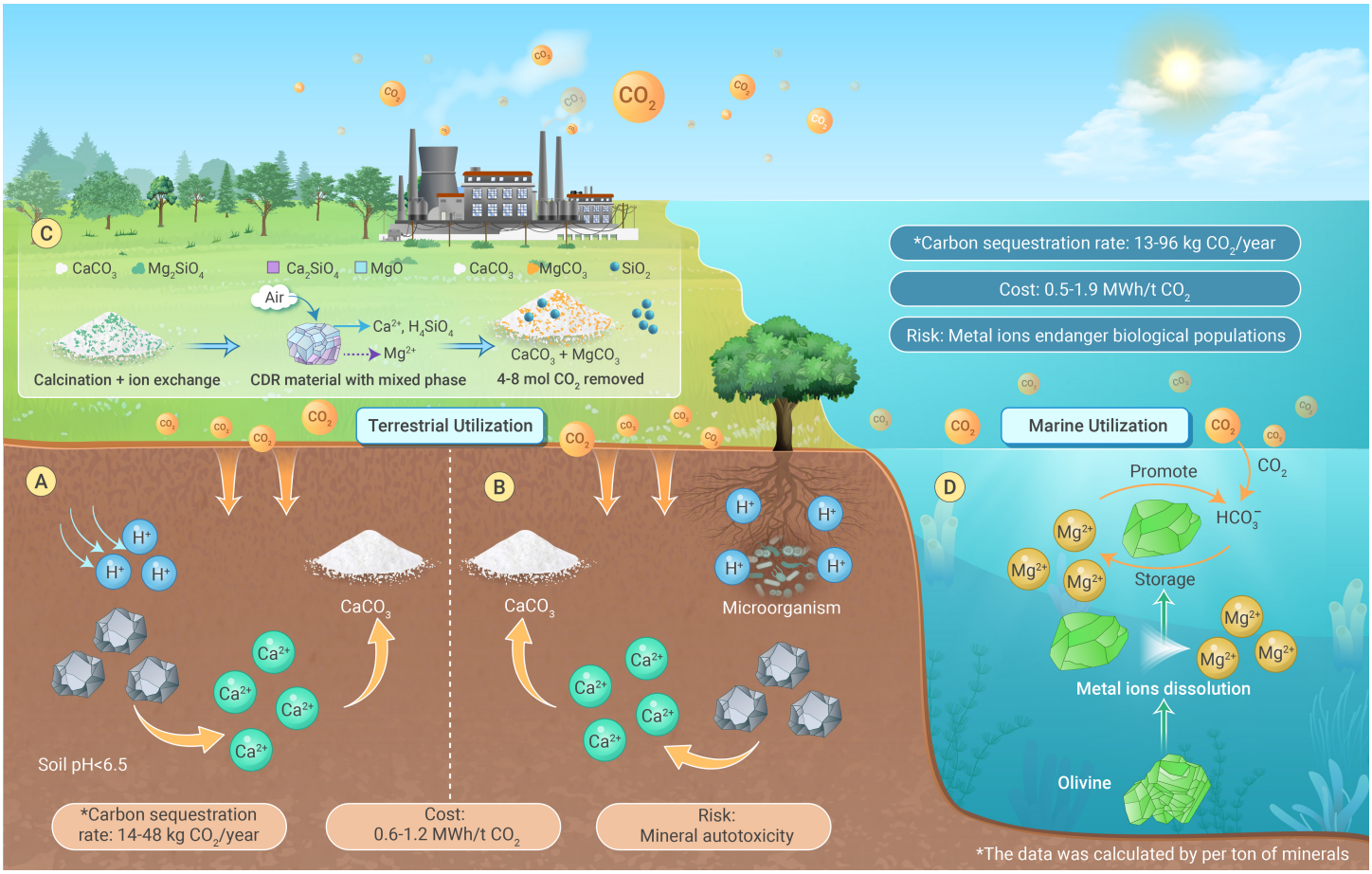

Figure 1. Methods to accelerate weathering rate (A) Acidic soil accelerates M^{2+} leaching. Reprinted with permission,[2] Springer Nature. (B) Plant roots and microorganism release organic acids to promote M^{2+} leaching. Reprinted with permission,[3] Springer Nature. (C) Ca^{2+}/Mg^{2+}heat exchange releases alkaline species. Reprinted with permission, [4] Springer Nature. (D) Seawater leaching ore alkaline cations. Reprinted with permission, [5] ACS Publications.

Natural minerals are difficult to react with CO_2 due to their solid form, and their natural weathering process is very slow. Under humid conditions, CO_2 can combine with water to form H_2CO_3. The alkaline metal ions released through mineral dissolution can react with H_2CO_3 to form carbonate precipitates, which can significantly improve the reaction rate. Therefore, promoting the leaching of alkaline elements from minerals represents a feasible approach to enhancing reaction rates. Previous study has shown that H^+ in the environment is beneficial for accelerating the dissolution of solid minerals and the leaching of alkaline metal ions. Kantzas et al.[2] used broken sili-

cate rocks to modify soil, enhance rock weathering, and achieve CO_2 removal (Figure 1A). They found that H^+ in the soil can accelerate the release of Ca^{2+} and achieve CO_2 sequestration. The pH of the soil can also be adjusted to promote crop growth. This method is suitable for acidic soils rich in H^+(pH<6.5). Kantzas et al's work[2] showed that implementing rock weathering in cultivable farmland in the UK can result in an annual CO_2 removal of 6-30 Mt, equivalent to 45% of the atmospheric removal required for the country to achieve net zero emissions. Taylor et al.[3] found that plant roots and microorganisms can release organic acids, which increase the concentration of H^+ in the surrounding environment (Figure 1B). The presence of H^+ promotes rock dissolution, subsequently releasing Ca^{2+}, which facilitates CO_2 sequestration. The research shows that idealized enhanced weathering scenarios over less than a third of tropical land could lower atmospheric CO_2 by 30–300 ppm by 2100. This method is suitable for tropical regions with abundant vegetation and microorganisms.

The primary application domain of enhanced weathering is the open ocean. However, the mechanisms governing marine olivine weathering and their implications for seawater-carbonate chemistry remain poorly constrained. Montserrat et al.[5] experimentally investigated mechanisms to enhance olivine weathering in marine environments for CO_2 sequestration (Figure 1D). Their study revealed that olivine dissolution significantly increased seawater alkalinity, driving CO_2 invasion and elevating dissolved inorganic carbon, thereby validating the fundamental feasibility of enhanced silicate weathering. Physical agitation methods accelerated dissolution rates by promoting particle-particle collisions and surface abrasion, as evidenced by SEM-EDX analyses showing rounded particle edges and preferential Mg leaching (20–30% reduction in Mg/Si ratios). Studies have demonstrated that during the seawater dissolution of olivine, divalent cations are preferentially released over silicon. Short-term experiments reveal nonstoichiometric dissolution of olivine, with initial dissolution rate constants for Mg being approximately 30 times higher than those for Si. This phenomenon is mechanistically linked to two factors: First, the crystal ionic radius of Mg^{2+} is comparable to those of other cations within the olivine lattice, enabling its rapid migration to the mineral surface through solid-state diffusion. Second, the formation of a silica-enriched, magnesium-depleted altered surface layer during initial dissolution stages markedly suppresses Si release, whereas cations are rapidly liberated via boundary-layer reactions.

A potentially viable strategy to accelerate the weathering rate would involve the targeted liberation of alkaline constituents from silicate minerals through specialized processing techniques. This approach facilitates the conversion of these constituents into hydroxides or oxides with significantly enhanced reactivity toward CO_2, thereby promoting more efficient carbon sequestration. Chen[4] et al. introduce a highly efficient thermal Ca^{2+}/Mg^{2+} exchange process to accelerate the mineralization rate of CO_2 using Mg-rich silicates (e.g., olivine, serpentine, and augite) (Figure 1C). $CaCO_3$ (limestone) or $CaSO_4$ was used to react with Mg-silicates at high temperatures (1200–1300°C), resulting in the formation of Ca_2SiO_4 and MgO. This transformation significantly enhances carbonation reactivity compared to natural silicates. When exposed to humid air, Ca_2SiO_4 rapidly reacts with CO_2 to form $CaCO_3$, while MgO partially carbonates into Mg-carbonates within weeks, whereas untreated Mg-silicates remain unreactive for over six months. More importantly, when subjected to 1 atm CO_2 at ambient temperature, the converted materials achieve complete carbonation within hours, forming $CaCO_3$ and soluble $Mg(HCO_3)_2$, demonstrating a dramatic increase in reaction kinetics. An energy assessment reveals that this process requires less than 1 MWh per ton of CO_2 removed, which is at least 50% lower than the leading direct air capture technologies. For the DAC cycle based on the $CaO/CaCO_3$ cycle, in the calcination stage alone, capturing each ton of CO_2 with 100% thermal efficiency requires 1.5 MWh of heat. This process far exceeds the energy consumed by calcination. By enhancing mineral weathering rates via high-temperature ion exchange, this method offers a scalable, energy-efficient alternative to current CDR technologies.

CONCLUSION AND PERSPECTIVE

In general, the natural minerals-based CDR technology demonstrates significant potential for carbon fixation and other advantages. By activating and releasing their alkalinity, natural minerals can be transformed into active oxides or hydroxides, thereby enhancing their carbon sequestration performance.

From a broader perspective, industrial by-products generated during production processes can also be classified as minerals, albeit those have been modified through human activities. Compared to natural minerals, these industrial by-products have undergone high-temperature treatment during the product manufacturing process, which results in a higher concentration of alkaline elements, thus possessing greater carbon sequestration potential. The potential for direct sequestration of CO_2 by industrial solid waste is approximately 310 million tons. If the carbonized products are subsequently used as building and construction materials, it could further indirectly reduce CO_2 emissions by about 3.7 billion tons. Therefore, researching the CDR potential of these industrial by-products is of great significance. Furthermore, the concentrations of CO_2 in industrial flue gases are usually several orders of magnitude higher, which theoretically enhances the reaction kinetics. Consequently, the use of natural minerals for CO_2 capture from industrial flue gases represents a promising and valuable area of research. Finally, while focusing on the carbon reduction effects of EW, it is essential to conduct more in-depth research to understand the technical risks involved. For example, whether heavy metal elements are leached during the EW process; whether the stability of storage will be affected by factors such as acidification, sediment remineralization, partial CO_2 release, and soil disturbance when the product enters the ocean remains a key question.; and whether it could have long-term impacts on the natural environment? Relevant research is needed to assess the long-term risks. We should not rush the large-scale application of EW to avoid counterproductive results.

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AUTHOR CONTRIBUTIONS

Yang Yang: Conceptualization, Writing – original draft, Writing – review & editing. Wenqing Xu: Conceptualization, Supervision, Funding acquisition. Zanbu Geng: Investigation, Writing – review & editing. Shaona Wang: Writing – original draft. Jun He: Writing – original draft. Dongke Zhang: Investigation, Conceptualization. Tingyu Zhu: Resources, Project administration, Supervision. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.