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CARBON MINERALIZATION: TRANSFORMING CONSTRUCTION & DEMOLITION WASTE SUSTAINIBILITY

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ABSTRACT

The construction and demolition (CD) industry's expanding waste streams and uncertainties about climate change have prompted new research on carbon sequestration and waste management techniques. Carbon mineralization appears to be a viable route, with the ability to convert embodied carbon in construction and demolition waste into stable carbonates via several physicochemical mechanisms instigating the development of uncontaminated recycled aggregates with enhanced mechanical and physical characteristics. Recognizing the importance of many concerns, this article emphasizes the importance of managing carbon emissions and garbage overflow from construction activities. A thorough innovative overview of carbon mineralization is developed by combining and critically analyzing a wide range of studies from existing literatures. The study also examines the environmental effects of these processes as well as the viability, scalability, and stability of the mineral products that are created over the long term. In addition, a comprehensive understanding of demolition waste kinds, chemical compositions, and carbon mineralization methods will be attained along with highlighting the environmental and economic possibilities of carbon mineralization processes for waste and CO_2 reduction. The findings not only shed light on existing challenges and research gaps but also act as a catalyst for stimulating innovation in sustainable waste management techniques. By emphasizing the crucial role of CO_2 mineralization and utilization, particularly utilizing alkaline solid wastes, the research positions these techniques as pivotal green technologies within the global portfolio for CO_2 mitigation. The scope of this research extends beyond the immediate concerns of waste management to encompass a broader vision of fostering green technologies that address climate change and advance the circular economy.

Keywords: *Carbon mineralization, construction and demolition waste, sustainable waste management.*

1. INTRODUCTION

Carbon mineralization, an intricate geochemical process, orchestrates the conversion of atmospheric carbon dioxide into stable mineral forms, fostering environmental sustainability. This complex phenomenon involves the catalytic mediation of minerals, propelling carbon sequestration to mitigate anthropogenic impacts on climate change. Mineral carbonation, also known as carbon dioxide (CO_2) mineralization, was originally introduced by Seifritz (Seifritz, W. CO_2 Disposal by Means of Silicates. Nature 1990, 345, 486., 1990), constitutes a pivotal component of CO2 capture, storage, and utilization (CCUS) technologies. Recognized as an effective strategy for mitigating climate change by reducing atmospheric greenhouse gas emissions (Carbon Dioxide Capture and Storage, 2005) , this process emulates the natural weathering of silicate minerals. In this artificial mimicry, CO_2 interacts with oxides of alkaline or alkaline-earth metals, such as calcium oxide (CaO) and magnesium oxide (MgO), culminating in the formation of carbonates, as depicted in the following reaction Formula (1) (Romanov et al., 2015) :

$$(Ca,Mg)SiO_{3\ (s)} + CO_{2(g)} \rightarrow (Ca,Mg)CO_3\ (s) + SiO_2\ (s) \ldots\ldots\ldots(1)$$

The chemical attributes of carbonates generated in the carbonation process exhibit stability, ensuring nearly permanent storage of CO_2 (Lackner et al., 1995). The reaction is inherently spontaneous, exothermic (Moazzem et al., 2013), and thermodynamically favourable. Various natural minerals, including serpentine (Teir et al., 2007; Nduagu et al., 2012), olivine (Kremer & Wotruba, 2020) , wollastonite (Tai et al., 2006) , basalt (Ayub et al., 2020), among others, undergo reactions with CO_2 to yield resilient carbonates. Industrial solid waste (ISW), characterized by high levels of CaO and MgO, serves as an additional source of alkalinity for CO_2 mineralization, with the added benefit of ameliorating environmental impacts through enhanced stability post-carbonation (Xie et al., 2016). Common ISW types encompass fly ash (Reynolds et al., 2014) (Bauer et al., 2011), steel slag (Eloneva et al., 2010) (Chang et al., 2012), carbide slag (R. Liu et al., 2020), phosphogypsum (Gan et al., 2016) (Ding et al., 2019), ore tailings (Power et al., 2014), etc.

A recent comprehensive review by Xie et al. (Pan et al., 2020a) delves into the advancements in CO_2 mineralization technologies concerning both natural ores and industrial solid wastes. The review spans fundamental science, engineering applications, and economic evaluations, projecting a widespread adoption of CO_2 mineralization technologies in conjunction with natural resource exploitation and industrial solid waste treatment in the foreseeable future (Pan et al., 2020a). Furthermore, the application of CO_2 mineralization introduces an industrial ecology approach in the ISW sector. It not only aids in the recovery of valuable metals but also facilitates the production of valuable chemicals. Particularly noteworthy is its potential near CO_2 point sources, where waste generated in proximity can be effectively treated through CO_2 mineralization technologies, offering a valuable solution for factories (Bobicki et al., 2012). Therefore, this research provides a comprehensive review of recent developments in emerging technologies for CO_2 mineralization through industrial solid waste (ISW). It offers an innovative overview of carbon mineralization, critically analyzing existing literature to assess environmental impacts, long-term viability, and economic possibilities. The study aims for a comprehensive understanding of demolition waste types and carbon mineralization methods, emphasizing their potential for sustainable waste and CO_2 reduction. The overview encompasses both theoretical principles and practical considerations, to enhance understanding among a broader international audience. This comprehensive overview is notably unique, as no such compilation has been reported until now.

2. CARBON MINERALIZATION PROCESS ROUTES

The pursuit of effective mineral carbonation technologies (MCT) to address CO_2 emissions has given rise to a multitude of process routes, each varying in complexity. This article aims to elucidate the evolving landscape of MCT process routes, drawing insights from earlier classifications proposed (Huijgen & Comans; Sipilä et al.)and presenting an updated version in Fig. 1.

2.1 Classification Framework

The identified process routes are systematically categorized into three distinct headings: 'ex-situ MCT,' 'in-situ MCT,' and 'other MCT routes.' The 'ex-situ MCT' paradigm encapsulates the original approach, involving aboveground carbonation of natural minerals and industrial alkaline wastes through industrial processes. This traditional methodology has been subject to extensive research and development efforts. In contrast, the 'in-situ MCT' paradigm represents a more recent advancement in the field. Diverging from conventional geological storage, in-situ MCT involves the injection of CO_2 underground under meticulously optimized conditions. The objective is to expedite the natural process of mineral carbonation, offering a novel and dynamic approach to carbon capture and storage. The 'other MCT routes' category serves as an umbrella for carbonation routes that do not neatly align with either ex-situ or in-situ classifications. This diverse set of approaches presents a spectrum of innovative strategies that warrant exploration and analysis. Fig. 1 serves as a visual aid, capturing the essence of the diverse process routes within the MCT landscape.

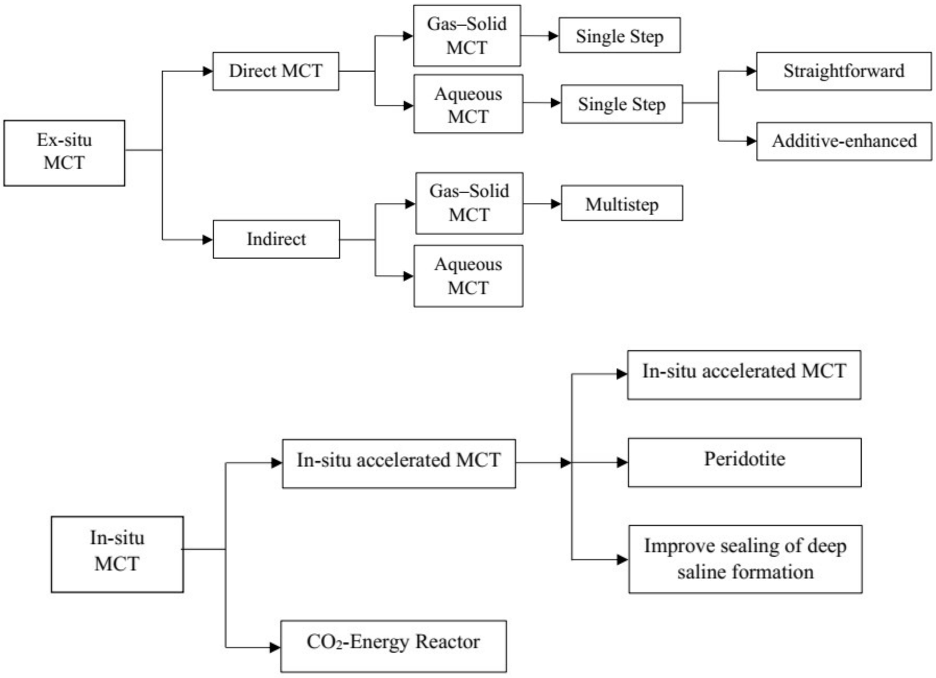
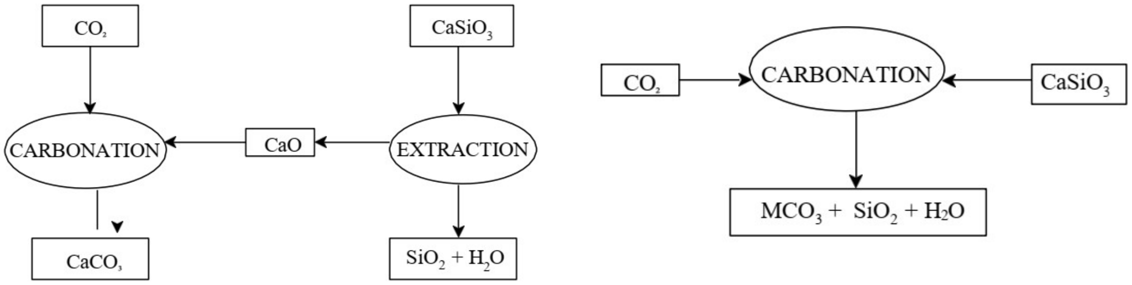


Figure 1: Visual Representation of MCT Process Routes (Huijgen & Comans)

As depicted in Fig. 1, the classifications of 'ex-situ MCT,' 'in-situ MCT,' and 'other MCT routes' offer a structured framework to comprehend the complexities inherent in this field.

2.2 Ex-situ MCT

The original approach to mineral carbonation technology (MCT) involves processing natural minerals and industrial alkaline wastes above ground using industrial chemical methods. This is called the "ex-situ MCT" route. The MCT process consists of two main steps: pre-treatment and sequestration. Pre-treatment involves mining, crushing, and milling the mineral-bearing ores to increase their surface area and reactivity for carbonation. There are two main types of ex-situ MCT processes: direct and indirect. In direct methods, the mineral is carbonated in a single step. In indirect methods, the reactive components (such as calcium or magnesium) are first extracted from the mineral and then carbonated separately. This yields a purer carbonate product. Fig.2 represents the basic principles of the direct and indirect carbonation methods.



Indirect Carbonation **Direct Carbonation**

Figure 2: Basic principles of the direct and indirect carbonation methods (Eloneva et al., 2008)

2.3 Direct Carbonation Routes

There are two ways to directly carbonate a mineral: either through a dry gas-solid reaction or by using an aqueous solution.

2.3.1 Gas Solid Route

The direct reaction of gaseous carbon dioxide (CO_2) with solid minerals or alkaline waste represents the most straightforward route within the realm of mineral carbonation technologies (MCT). Despite its inherent simplicity in process design and its superior ability to harness the heat generated during carbonation reactions, this approach has faced a marked decline in interest due to its sluggish reaction rates (equation 02).

$$(Ca, Mg)SiO_3\ (s) + CO_2(g) \rightarrow (Ca, Mg)CO_3\ (s) + SiO_2 \ldots \ldots \ldots (2)$$

Presently, only a limited number of research groups, notably those led by (Reddy et al., 2010) and (Baciocchi et al., 2009), remain engaged in this method utilizing reactive wastes. The primary impediment to the widespread adoption of direct gaseous CO_2 mineral carbonation lies in the substantial hindrance posed by exceedingly slow reaction kinetics, particularly concerning calcium/magnesium silicates (Lackner et al., 1995, 1997). Despite its potential net exothermic heat effect, as indicated by an energy analysis of direct dry carbonation of magnesium silicates (Zevenhoven & Kavaliauskaite, 2004), this route has failed to gain momentum beyond the research stage. Experimental endeavors in the realm of direct dry carbonation of calcium/magnesium silicates, even under elevated pressures (Zevenhoven & Kohlmann), have yielded carbonation conversions that remain notably insignificant. However, this strategy, while potentially improving carbonation rates, is marred by its inherent energy-intensive nature (Zevenhoven & Kohlmann). In essence, the direct gaseous CO_2 mineral carbonation route, despite its simple process design and heat utilization advantages, grapples with formidable challenges stemming from lethargic reaction kinetics.

2.3.2 Aqueous Carbonation

Direct aqueous carbonation stands out as a multifaceted process encompassing three concurrent mechanisms within a singular reactor. The primary mechanism involves the dissolution of carbon dioxide in the water phase, establishing a mildly acidic milieu where bicarbonate (HCO_3) prevails as the predominant carbonate species (equation 03).

$$CO_{2(g)} + H_2O_{(l)} \rightarrow H_2CO_{3(aq)} \rightarrow H_{(aq)}^{+¿+HCO_{3(aq)}^{-¿¿}¿} \ldots \ldots \ldots (3)$$

Secondly (equation 04), Ca/Mg leaches from the mineral matrix, facilitated by the protons present:

$$(Ca/Mg)\, silicate\, s_{(s)} + 2H_{(aq)}^{+¿¿} \rightarrow (Ca/Mg)_{(aq)}^{2+¿¿} + SiO_{2(s)} + H_2O_{(l)} \ldots \ldots \ldots (4)$$

Finally (equation 05), magnesium or calcium carbonate precipitates:

$$(Ca/Mg)_{(aq)}^{2+¿+HCO_{¿}^{-¿\rightarrow(Ca/Mg)CO}+H_{(aq)}^{+¿¿}¿}¿ \ldots\ldots\ldots (5)$$

This intricate interplay necessitates a nuanced understanding of the underlying kinetics and operational parameters to optimize the efficiency of the process.

2.3.2.1 Rate-Limiting Silicate Dissolution:

In the realm of direct aqueous carbonation, the dissolution of silicate emerges as the pivotal, rate-limiting step.This pursuit has been characterized by a diverse array of additives and meticulous adjustments to operating conditions, encompassing temperature, pressure, CO_2 concentration, solid-to-liquid ratio, and particle size. Recognizing the critical importance of these factors, standard optimal process conditions, as applied at ARC, include a finely ground feedstock (80% below 37 µm), a CO_2 pressure of 150 atm, and an operational temperature of 185°C (Gerdemann et al.) .

2.4 Indirect Carbonation Routes

Indirect carbonation entails separating tasks such as extracting Ca and/or Mg from the feedstock, dissolving CO_2 (in the context of aqueous carbonation), and precipitating carbonate materials, either as discrete steps or within disparate reactors. Numerous proposed indirect carbonation routes leverage different minerals, offering a diversified array of strategies within the broader spectrum of mineral carbonation technologies.

2.4.1 Multi-Step Gas–Solid Route

The conversion of calcium/magnesium (Ca/Mg)-silicates into $(Ca/Mg)(OH)_2$, followed by subsequent direct dry carbonation, represents an intriguing avenue in mineral carbonation processes. The methodologies proposed by (Zevenhoven et al., 2008) , elucidates the dynamics of producing reactive $Mg(OH)_2$ and its subsequent carbonation, presenting two alternative routes for serpentine carbonation.

$$Mg_3Si_2O_5(OH)_{4(s)} \rightarrow 3MgO_{(s)}+2SiO_{2(s)}+2H_2O_{(l)} \ldots\ldots\ldots (6)$$

$$Mg_3Si_2O_5(OH)_{4(s)}+H_2O_{(l)} \rightarrow 3Mg(OH)_{2(s)}+2SiO_{2(s)} \ldots\ldots\ldots (7)$$

2.4.2 Chemical Processes:

The production of free MgO or $Mg(OH)_2$ from serpentine marks the initial phase in magnesium silicate carbonation, as direct carbonation of silicate at a sufficient chemical rate proves challenging (Zevenhoven et al.,2008) The chemistry involved in the production of more reactive $Mg(OH)_2$ necessitates the input of water (as steam), a step initially discarded due to unfavourable thermodynamics. However, an alternative route was proposed, involving the combination of reactions, ultimately leading to the desired $Mg(OH)_2$.

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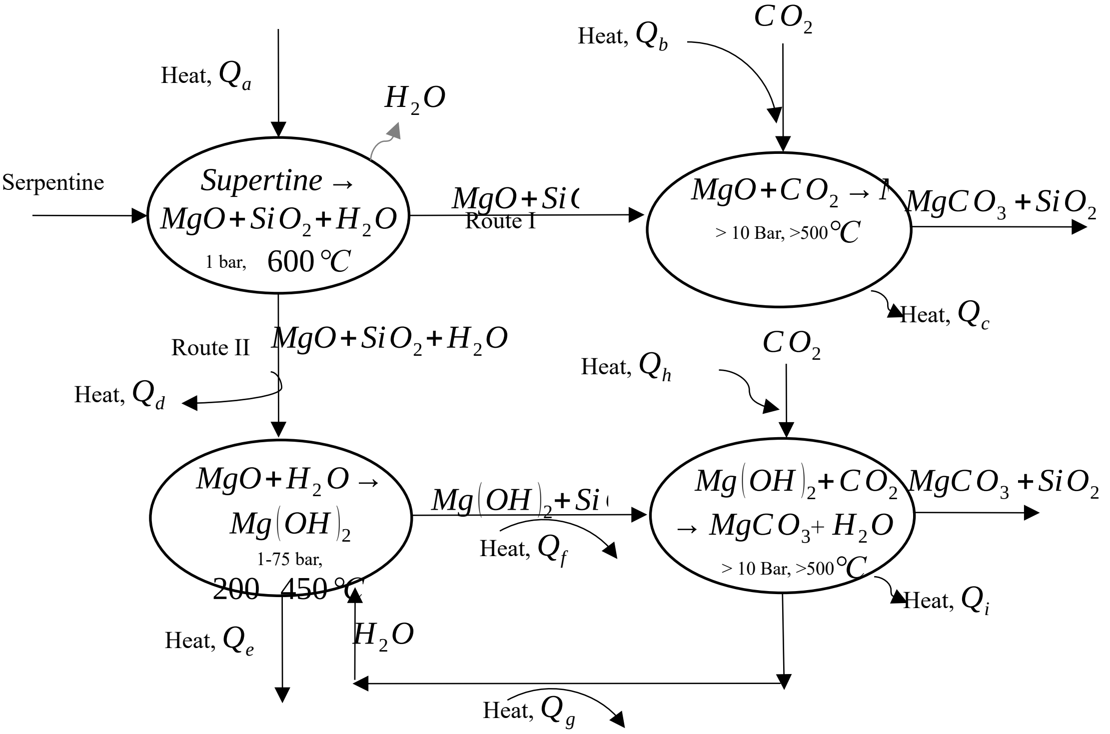
$$MgO(s)+H_2O(l) \rightarrow Mg¿\ldots\ldots\ldots (8)$$

$$Mg(OH)_2(s)+CO_2 \rightarrow MgCO_3(s)+H_2O(l)\ldots\ldots\ldots (9)$$

2.4.3 Alternative Routes:

Figure 3: Two alternative routes for serpentine carbonation via (Zevenhoven et al., 2008)



(Zevenhoven et al., 2008) systematically compared two alternative routes for serpentine carbonation: Route 1, a two-step process via MgO extraction followed by MgO carbonation, and Route 2, a three-step process involving MgO extraction, MgO hydration, and subsequent $Mg(OH)_2$ carbonation. Both routes were analyzed with a focus on optimizing heat stream energies to discern the most efficient and effective strategy. Fig 3. Shows two alternative routes for serpentine carbonation via MgO or $Mg(OH)_2$

2.4.3.1 Route 1 Dynamics:

In Route 1, MgO production in an atmospheric reactor precedes carbonation at elevated pressure. The choice of elevated pressure is strategic, allowing for stable $MgCO_3$ at higher temperatures where chemical kinetics are accelerated. The production of MgO from serpentine requires a temperature of 600°C, aligning with the subsequent carbonation temperature under elevated CO_2 pressure.

2.4.3.2 Route 2 Dynamics:

Conversely, Route 2 entails a three-step process involving MgO production, followed by MgO hydration and subsequent $Mg(OH)_2$carbonation. The preference for elevated pressure in this route is similarly driven by the desire for stable solid products at higher temperatures conducive to enhanced chemical kinetics. Notably, (Zevenhoven et al., 2008)assert that Route 2 is not only preferable in terms of energy efficiency but also exhibits faster carbonation kinetics.

The exploration of two distinct routes for serpentine carbonation sheds light on the intricate balance between thermodynamics, kinetics, and energy efficiency. The comparative analysis presented herein underscores the potential advantages of Route 2, emphasizing its merits in achieving both optimal energy utilization and expedited carbonation kinetics.

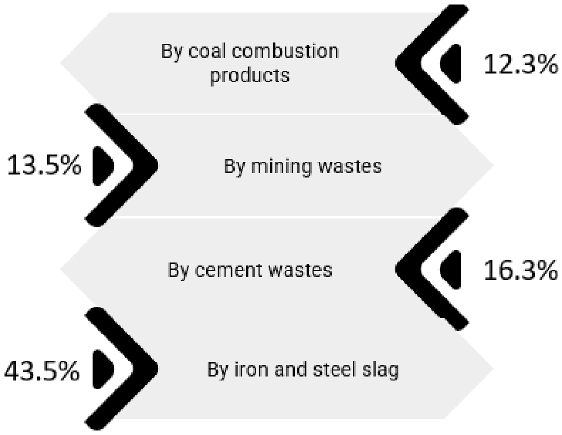
3. CARBON MINERALIZATION PROCESS ROUTES

Feedstocks	Output (Mt/y)	CaO Wt.%	MgO Wt.%	Main Active Components
Blast furnace slag	390	30 50	5 15	Gehlenite ($Ca_2Al_2SiO_7$¿ Akermanite ($Ca_2MgSi_2O_7$¿
Steel slag	240	30 60	3 15	C_2S, C_3S, Free CaO, C_2F, forsterite (Mg_2SiO_3)
Coal fly ash	750 1000	5 50	0 10	Lime (CaO) Portlandite ($(Ca(OH)_2)$
Waste gypsum	300	27 33	¿1	$CaSO_4.2H_2O$

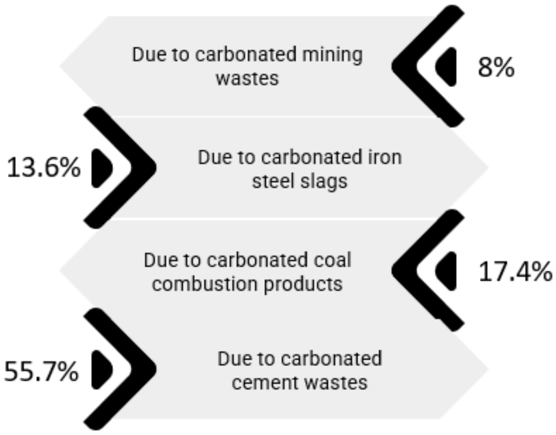
Iron and steel slags, coal fly ash, and waste gypsum stand out as the predominant industrial solid wastes, showcasing distinctive physicochemical properties as outlined in Table 1. Coal fly ash, with a global output reaching up to 1000 million tons annually, commands the highest production due to the substantial demand for fossil fuels. However, the carbonation capacity of coal fly ash varies significantly, contingent upon its CaO content, predominantly derived from low ash content coal combustion such as bituminous coal. Mullite ($Al_6Si_2O_{13}$) and quartz (SiO_2) constitute the primary mineral phases in coal fly ash, presenting challenges for optimal CO2 mineral carbonation (W. Liu et al., 2021) .

Table 1. Comparison of the different wastes for mineral carbonation (W. Liu et al., 2021).

Iron and steel making slags follow closely as the second-largest industrial waste output, accounting for approximately 630 million tons globally. Figure 4a illustrates the direct CO_2 reduction percentages attributed to various alkaline solid wastes, with mineralization of iron and steel slags contributing the highest share at 43.5%. Cement wastes, mining wastes, and coal combustion ashes follow suit at 16.3%, 13.5%, and 12.3%, respectively. (Pan et al., 2020b) Conversely, Figure 4b highlights the substantial indirect CO2 reduction potential through product utilization, estimating around 3.7 billion tons of CO_2 emissions avoided annually by employing carbonated products as construction materials. Carbonated cement/concrete wastes lead in indirect CO_2 reduction at 55.7%, followed by carbonated coal combustion products (17.4%), iron and steel slags (13.6%), and mining wastes (8.0%) (Pan et al., 2020b).

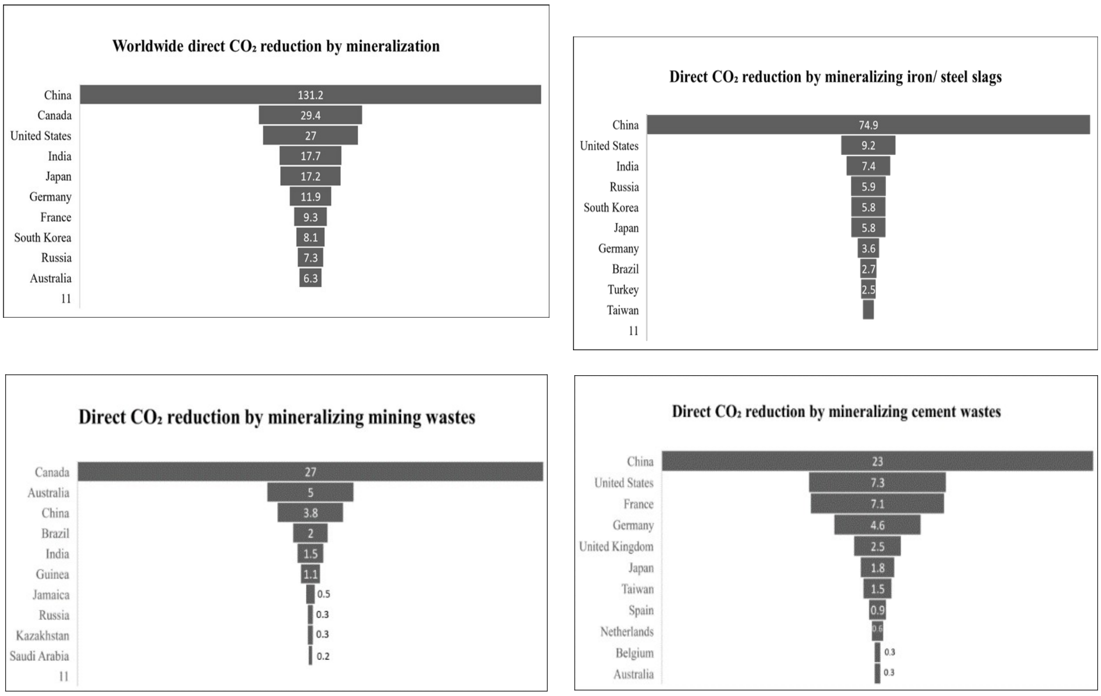


(a)



(b)

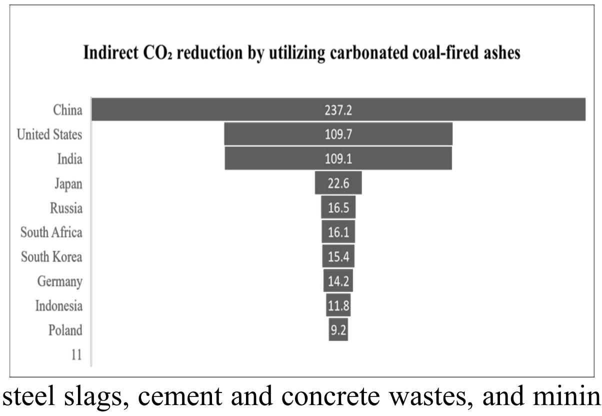
Figure4. Contribution by different alkaline solid wastes in global CO_2 reduction. (a) Percentage of the amounts of direct CO_2 reduction due to mineralization and (b) indirect CO_2 reduction by carbonated product utilization (Pan et al., 2020b)

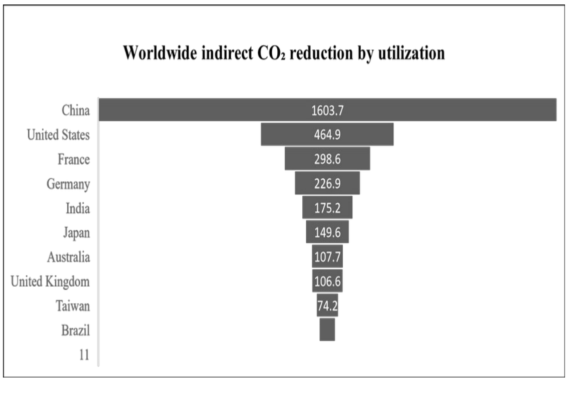


Globally, the cumulative reduction achieved through CO_2 mineralization and utilization with alkaline solid wastes approximates 4.02 billion tons of CO_2 annually. This translates to a noteworthy reduction in global anthropogenic CO_2 emissions, constituting approximately 12.5%. For context, this reduction surpasses the anticipated global impact of carbon capture and storage, a pivotal CO_2 mitigation measure projected to contribute between 5.5 to 8.2 billion tons by 2050.

Figure 5: Summary of global CO_2 reduction amounts by mineralization (direct) industrial solid wastes (Pan et al., 2020b)

Fig. 5 and Fig. 6 provide a comprehensive overview of the potential direct and indirect reductions achieved through CO_2 mineralization and utilization across different countries. China emerges as a frontrunner, contributing over four times more to global direct CO_2 reduction than any other country. The top ten countries collectively account for 87.1% of global direct CO_2 reduction, with iron and steel slags, cement and concrete wastes, and mining and mineral processing wastes being the primary contributors. (Pan et al., 2020b) Similarly, for indirect CO_2 reduction from carbonated product





utilization, China leads with the world's largest potential, with the top ten countries representing 89.2% of global indirect CO_2 reduction. (Pan et al., 2020b) The primary contributors in this category include carbonated cement and concrete wastes, coal combustion ashes, and iron and steel slags (Pan et al., 2020b).

Figure 6: Summary of global CO_2 reduction amounts by utilization of industrial solid wastes.

4. UNDERSTANDING OF THE SUSTAINIBILITY OF CO_2 MINERALIZATION TECHNOLOGIES (MDPI)

Implementing CO_2 mineralization technologies, utilizing industrial solid waste (ISW) and other carbon capture, utilization, and storage (CCUS) methods, requires a thorough assessment before large-scale deployment. Key considerations include:

4.1 Technical Feasibility:

- Pilot projects should address uncertainties in technology development.
- Collaboration among academia, research institutes, and enterprises is crucial for advancements.
- Establishing a clear technology roadmap is essential for overcoming barriers.

4.2 Economic Feasibility:

- Despite high initial costs, opportunities for improvement exist in CO_2 mineralization using ISW.
- Comprehensive life cycle cost assessments, covering resource prices, energy, manpower, and various processes, are vital.

4.3 Environmental Impacts and Risks:

- Life cycle assessment (LCA) should be applied for a comprehensive environmental impact evaluation.
- Consideration of energy penalty and regional energy supply structures is crucial.
- Environmental risk assessments throughout the project life cycle, including construction, operation, and decommissioning, are necessary for certification and approval.

5. CURRENT RESEARCH GAP AND CHALLENGES

Current knowledge gaps on carbon mineralization include the need for accurate kinetic models to describe the process and factors affecting it. There is also a need for further research on the optimization of process parameters and equipment design for scale-up applications of CO_2 mineral carbonation. Additionally, the recovery of high-value products during the carbonation process needs to be explored to improve the economic viability of the technology. Table 2 shows the current research gaps and the reasons behind those.

Table 2: Current Research gaps & Challenges

Understanding Mineral Carbon Kinetics	The kinetics of carbon mineralization reactions, especially under natural conditions, are not fully understood. Research is needed to determine the rate at which minerals can absorb and sequester carbon dioxide, and how different factors (e.g., temperature, pressure, mineralogy) influence these rates.
Optimization of Reaction Conditions	Identifying optimal conditions for mineral carbonation is crucial for maximizing the efficiency of the process. This involves determining the most suitable minerals, particle sizes, and reaction temperatures and pressures for effective carbon sequestration
Monitoring and Verification Techniques	Developing reliable and cost-effective monitoring techniques to assess the progress of mineral carbonation in real-time is essential. This includes methods for detecting changes in mineral composition and assessing the stability of carbonates formed during the process.
Economic Viability and Life cycle Analysis	Conducting comprehensive economic assessments and life-cycle analyses to determine the overall feasibility and environmental impact of carbon mineralization processes. This includes evaluating the costs associated with mining minerals, transportation, and the long-term storage of carbonates
Mineral Availability and Resource Constraints	Assessing the availability of suitable minerals for large-scale carbon mineralization and potential resource constraints. This involves considering the geographic distribution of minerals, mining practices, and the environmental impact of extraction

6. CONCLUSION

The burgeoning challenges posed by the construction and demolition (CD) industry's expanding waste streams and the escalating uncertainties surrounding climate change demand innovative and sustainable solutions. The research spotlighted in this article underscores the fact that carbon mineralization emerges as a promising avenue, offering the potential to transform embodied carbon in CD waste into stable carbonates through various physicochemical mechanisms. Importantly, the study delves into the viability, scalability, and long-term stability of the mineral products resulting from carbon mineralization. By doing so, it sheds light on the potential of this technology to contribute to waste and CO_2 reduction on a global scale. The recognition of different demolition waste types, their chemical compositions, and the various carbon mineralization methods employed adds depth to the discussion. However, Current knowledge gaps on carbon mineralization include the need for accurate kinetic models to describe the process and factors affecting it. There is also a need for further research on the optimization of process parameters and equipment design for scale-up applications of CO_2 mineral carbonation. By offering insights into potential challenges and identifying research gaps, it serves as a catalyst for stimulating innovation in sustainable waste management techniques. The intention is to contribute to a more comprehensive understanding of the research domain and emphasize the importance of CO_2 mineralization and utilization using alkaline solid wastes as a crucial green technology within the strategic global portfolio for CO_2 mitigation.

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