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Review of Carbon Mineralization of Industrial Solid Wastes: Opportunities and Challenges

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Abstract

Global CO_2 emissions have exceeded 35 billion tons annually, intensifying climate change and increasing the demand for scalable carbon mitigation technologies. Mineral carbonation using industrial solid wastes such as steel slag, aluminum dross, fly ash, and flue gas desulfurization (FGD) gypsum has emerged as a sustainable approach for permanent CO_2 sequestration while simultaneously valorizing industrial residues. This review critically evaluates direct and indirect mineral carbonation processes using industrial wastes, with emphasis on carbonation mechanisms, reactor configurations, operating conditions, industrial symbiosis, and value-added by-product generation. Comparative analyses of reactor systems, including rotating packed bed (RPB), slurry, and autoclave reactors, are also presented. Steel slag-based aqueous carbonation systems exhibited the highest CO_2 uptake capacity (260–288 kg CO_2 t^{-1} slag), while gypsum-based systems achieved conversion efficiencies of 90–95%. Indirect carbonation of steel slag enabled calcium leaching efficiencies of ~80% and precipitated calcium carbonate (PCC) purities up to 99.5%. Fly ash-derived sorbents demonstrated CO_2 removal efficiencies approaching 70% following activation, whereas aluminum dross enabled rapid carbonation under ambient conditions (<1 h). Reactor intensification using RPB systems significantly enhanced gas–liquid–solid mass transfer and reduced residence times compared with conventional slurry and autoclave reactors. Large-scale implementation remains constrained by energy-intensive CO_2 compression, heat management challenges, slurry mixing limitations, feedstock heterogeneity, and reactor scale-up complexity. Variability in flue gas composition, particularly SOx, NOx, and moisture content, further influences carbonation efficiency and reaction pathways. Future research should focus on wastewater-assisted carbonation, solvent recycling, pilot-scale industrial symbiosis, and integrated resource recovery systems combining CO_2 sequestration with PCC and metal recovery.

Keywords: CO_2 Emissions, Climate Change, Mineral Carbonation, Industrial Solid Wastes, CO_2 sequestration.

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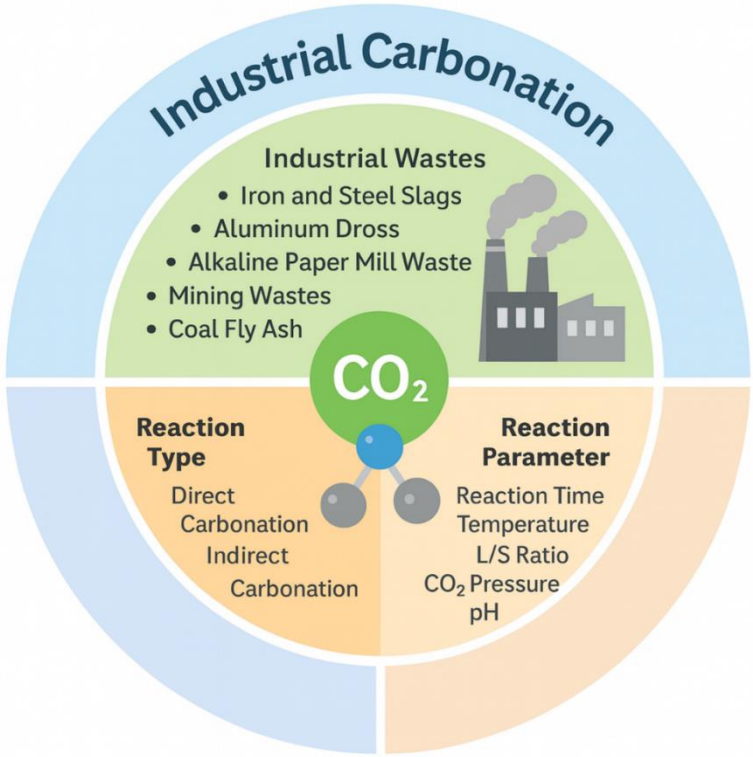
Graphical abstract



1. Introduction

Recent years have witnessed an alarming rise in greenhouse gas emissions, with carbon dioxide (CO_2) emerging as the most significant contributor to climate change. Current global CO_2 emissions have exceeded 35 billion tons annually and are projected to double by 2050, intensifying the urgency for mitigation strategies (Baena-Moreno *et al.,* 2019; M. Lee *et al.,* 2016; Zhang *et al.,* 2020). According to the International Energy Agency, Carbon Capture, Utilization, and Storage (CCUS) technologies must account for 15% of the required emissions reductions to achieve carbon neutrality by 2070. Within the CCUS framework, mineral carbonation has emerged as a promising approach for CO_2 sequestration, offering both environmental and economic advantages (Cui *et al.,* 2019; Romero-Hermida *et al.,* 2017). This process leverages natural ores or industrial waste materials containing alkali metals, such as calcium and magnesium, to convert CO_2 into stable carbonates for permanent sequestration. While traditional geological storage approaches, while effective, are often constrained by cost, scalability, and risks associated with potential CO_2 leakage. This has led to increased interest in mineral carbonation, a process that chemically converts CO_2 into stable carbonate minerals. Unlike geological storage, mineral carbonation offers the dual advantage of permanent carbon sequestration and the potential for producing valuable by-products (Baena-Moreno *et al.,*, 2022; Veetil *et al.,*, 2020). Nevertheless, the low reactivity of natural minerals such as serpentine and olivine has been a significant bottleneck, necessitating energy-intensive activation methods and large-scale reactors that increase costs and environmental burdens (Pan *et al.,* 2012).This inevitably results in the need for enormous reactors and labor and resource intensive operations to drive the carbonation reaction. In addition, the required milling and activation phases for natural ores, which are typically carried out at high temperatures and pressures, would have a significant negative influence on the surrounding environment, which might potentially nullify the benefits of CO_2 reduction. In this context, industrial solid wastes such as slags, ashes, and residues have emerged as promising alternatives for CO_2 mineralization. These wastes, characterized by their high basicity, intrinsic alkalinity, and widespread availability near industrial sites, exhibit significantly higher reactivity compared to natural minerals, making them ideal candidates for cost-effective and scalable carbon capture solutions (Ke *et al.,* 2023; Pan *et al.,* 2012; Wang *et al.,* 2021). The mineralization of carbon dioxide by employing wastes containing alkaline materials is thermodynamically suitable and has quick reaction kinetics at circumstances that are close to ambient.

Although an activation procedure for solid wastes could be required to remove the product layer that is on the surface of the particles, the required parameters are often far more lenient than those for natural ores (Lee *et al.,* 2016; Wang *et al.,* 2021; Zhao *et al.,* 2019).Worldwide available industrial solid wastes for CO_2 mineralization and utilization include iron, steel and aluminum slags (Ho *et al.,* 2022; Jones *et al.,* 2006; Xie *et al.,* 2022), coal-fired

products (Baena-Moreno *et al.,* 2019), fuel combustion products (Xie *et al.,* 2022), mining/mineral processing wastes (Baena-Moreno *et al.,* 2022), incinerator residues (Baena-Moreno *et al.,* 2022), cement/concrete wastes (Wang *et al.,* 2019) and pulp/paper mill wastes (Pöykiö and Nurmesniemi. 2008). The steel, aluminum, and cement industries are the largest contributors to industrial CO_2 emissions due to the large volumes of alkaline solid wastes they discharge into the environment throughout their energy and resource-intensive production processes (Ho *et al.,* 2022). In particular, the stability and re-utilization of alkaline solid wastes are critical challenges for industries. This is because alkaline solid wastes are chemically unstable and contain substantial amounts of calcium oxide and/or magnesium oxide. These reactive ingredients, when exposed to water, can undergo an accelerated carbonation reaction with flue gas CO_2 to create carbonates; this process mimics natural weathering (Cui *et al.,* 2019; Ho *et al.,* 2022; Reddy *et al.,* 2019).The production of Aluminium and steel necessitates significant energy consumption and generates substantial waste and by-products, including carbon dioxide (CO_2), metallurgical slag, and wastewater (Ho *et al.,* 2022). Enhancing the collection and disposal of waste generated during production will yield beneficial outcomes for the environment and resource efficiency. Steel slag can be classified into many categories according to the smelting method employed in its production. Examples include Electric Arc Furnace Slag, Basic Oxygen Furnace Slag, Argon Oxygen Decarburisation Slag, Continuous Casting Slag and Ladle Furnace Slag (Ibrahim *et al.,* 2019). The majority of steel slag consists of dicalcium silicate ($2CaOSiO_2$), tricalcium silicate ($3CaOSiO_2$), free calcium oxide (CaO), and iron oxide (FeO/Fe_2O_3)(Baena-Moreno *et al.,* 2022; Polettini, Pomi, and Stramazzo 2016; Zhao *et al.,* 2018). Steel slag is produced at a global annual rate of about 130 million tons (Mohammadian *et al.,* 2015; Reddy *et al.,* 2019; Xie *et al.,* 2022), with the most majority of it disposed of in landfills, where it consumes precious cropland and pollutes groundwater and soil. Steel slag has a high carbonization activity because of its high concentration of alkaline salts and CaO, which allows the process to be carried out in the presence of water at room temperature and pressure. Industrial alkaline solid wastes, such as sources of calcium or magnesium oxide, are suitable CO_2 sequestration materials due to their abundance and inexpensive cost. These minerals don't necessitate any further mining or raw material use because of their high calcium content and association with CO_2 point source emissions. Furthermore, the chemical stability of these solid wastes is typically lower than that of minerals with a geological origin (He *et al.,* 2021; Siriwardena, 2015).

This review focuses to address the critical gaps in the current understanding and utilization of industrial solid wastes for CO_2 sequestration. Particularly focusing on the carbonation of aluminum dross and steel slags, it explores the mechanisms, challenges, and opportunities associated with transforming these industrial by-products into valuable resources. Furthermore, this work highlights the novelty of integrating waste carbonation with emerging concepts such as industrial symbiosis, where CO_2 emissions and solid wastes are co-processed to create economically valuable by-products. It involves integration of CO_2-emitting industries with sectors that generate alkaline metallurgical and industrial wastes, enabling waste and emissions from one process to become valuable inputs for another. Calcium- and magnesium-rich residues such as steel slag, red mud, cement kiln dust, and fly ash can react with captured CO_2 through mineral carbonation to form stable carbonate minerals. This approach allows permanent CO_2 sequestration while simultaneously reducing the environmental burden associated with waste disposal, transforming industrial by-products into useful raw materials. The insights provided here are intended to guide future research and development efforts toward scalable, cost-effective, and environmentally sustainable carbon capture technologies.

1.1. *Carbon sequestration of natural mineral*

Carbon sequestration in minerals, commonly known as carbonation or sequestration of minerals (Ke *et al.,* 2023; Zhao *et al.,* 2019), is a procedure that involves the use of minerals that have a high affinity for CO_2 in order to sequester carbon. Because of its potential to lessen monetary strain and add to long-term CCS strategies, it has been the subject of intensive research in recent years (Jones *et al.,* 2006; Romero-Hermida *et al.,* 2020; Wang *et al.,* 2021). During the process, carbon dioxide (CO_2) is fixed as thermodynamically stable and environmentally benign carbonate minerals in materials containing alkali or alkaline earth metal oxides or hydroxides (Equ 1 and 2) (Madhav *et al.,* 2023; K. R. Reddy *et al.,* 2019; Wang *et al.,* 2021). Since storage is considered permanent, there is no need for post-storage monitoring to take place. In addition, considering carbonation is exothermic, it is hypothesized that the process might be used to generate usable energy if carried out at sufficiently high temperatures. Earth's existing supply of alkaline earth metal oxides is sufficient to permanently store all the carbon dioxide that could ever be released because of burning fossil fuels. Carbon dioxide (CO_2) can also be stored through mineral carbonations in areas lacking access to geological storage sites (Yildirim and Prezzi 2011). Direct carbonation involves the direct reaction of alkaline solid phases with gaseous or dissolved CO_2. In aqueous systems, the process generally proceeds through three major stages: CO_2 dissolution, alkaline ion leaching, and carbonate precipitation.

Step 1: CO_2 Dissolution

$$CO_2(g) + H_2O(l) \leftrightarrow H_2CO_3(aq) \quad (1)$$

Step 2: Carbonic Acid Dissociation

$$H_2CO_3(aq) \leftrightarrow HCO_3^- + H^+ \quad (2)$$

$$HCO_3^- \leftrightarrow CO_3^{2-} + H^+ \quad (3)$$

Step 3: Calcium Dissolution from Steel Slag

$$CaO(s) + H_2O(l) \rightarrow Ca^{2+} + 2OH^- \quad (4)$$

Step 4: Carbonate Precipitation

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3(s) \quad (5)$$

$$CaO + CO_2 \rightarrow CaCO_3, \ \Delta H = -179\,kJ\,mol^{-1} \quad (6)$$

The same reaction path way can be sought for Magnesium oxides direct carbonation as well.

$$MgO + CO_2 \rightarrow MgCO_3, \Delta H = -188\,kJ\,mol^{-1} \quad (7)$$

According to Zhao *et al.,* 2020, the most prevalent alkali and alkaline metal oxides found in nature are magnesium oxide (MgO) and calcium oxide (CaO). Magnesium oxide (MgO) and calcium oxide (CaO) account for around 2.1 and 2.2 mol% of the earth's crust, respectively (Zhao *et al.,* 2020). MgO and CaO, on the other hand, are never found free in nature; rather, they are always bound up as silicates. Magnesium silicates, like as serpentine and olivine, play a significant role in the mineral carbonation process. According to Ruschi *et al.,* 2020, rock formations that contain these minerals frequently have substantial concentrations of magnesium oxide (usually between 30 and 60 weight percent of MgO), and as a result, they are easy to obtain. It is possible for magnesium and calcium silicate ores to undergo spontaneous carbonation, also known as natural weathering or indirect carbonation; however, the kinetics of this process under ambient circumstances are much too slow to serve as the basis for a commercial process. Despite the fact that it produces less heat, the carbonation of magnesium and calcium silicates is nevertheless considered to be exothermic. Improving the carbonation kinetics is one of the most difficult challenges associated with developing a technology for the commercial carbonation of minerals (Ruschi *et al.,* 2020). Indirect carbonation separates calcium extraction and carbonation into independent stages, enabling improved process control and higher PCC purity.

Step 1: Calcium Extraction

$$CaSiO_3(s) + 2NH_4Cl(aq) \rightarrow CaCl_2(aq) + SiO_2(s) + 2NH_3(aq) + H_2O(l)$$

Step 2: Carbonation and PCC Formation

$$CaCl_2(aq) + CO_2(g) + H_2O(l) \rightarrow CaCO_3(s) + 2HCl(aq)$$

Indirect carbonation generally provides higher carbonation efficiency and superior PCC purity because dissolution and precipitation are independently optimized. However, solvent regeneration and extractant recycling significantly affect economic feasibility and environmental sustainability.

The extraction and processing of the enormous quantities of raw material that are essential for an operation carried out on an industrial scale both need a significant amount of energy. Three to eight tons fewer tons of carbon dioxide are released into the atmosphere whenever a ton of coal is burned in a power plant, but this needs the mining of three to eight tons of mineral (and grinding it to seventy-five millimeters). According to (Pasquier *et al.,* 2016) grinding the feedstock to 37 mm would account for 75% of the energy penalty imposed on the process of power generation by an industrial-scale mineral carbonation operation based on the NETL method. This was determined by determining how much energy was required to grind the feedstock. Using these calculations, it was anticipated that the entire cost of carbon dioxide (CO_2) sequestration would be between $50 and $100 per metric ton, which is approximately ten times the cost of geological storage currently. O'Connor's estimations are still relied on as the authorized best-case scenario projected costs for mineral carbonation by a number of organizations, including the International Energy Agency and the Intergovernmental Panel on Climate Change, among others (Baena-Moreno *et al.,* 2023; Khudhur *et al.,* 2022; Meng *et al.,* 2022; Sanna *et al.,* 2014).

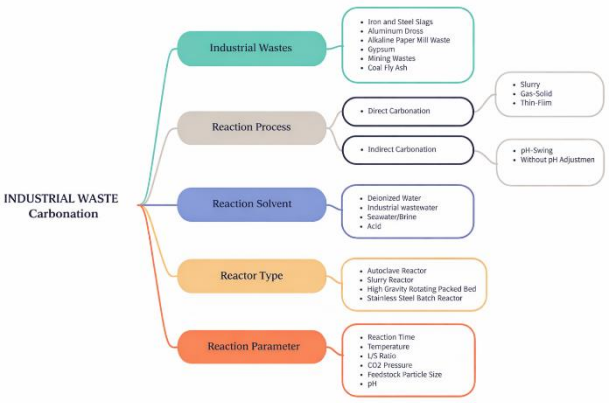


Figure 1. Structure Diagram of Industrial Wastes Carbonation.

1.2. *Carbon sequestration using industrial wastes*

Materials that are appropriate for CO_2 sequestration include industrial alkaline solid wastes, such as calcium or magnesium oxides, because of great availability of such mineral feedstock and low cost. Because the feedstock mineral is close to the CO_2 emission point, this method is cost-effective and energy-efficient for industries, allowing for greater CO_2 sequestration potential at a lower economic burden (Cui *et al.,* 2019; Romero-Hermida *et al.,* 2017; Sanna *et al.,* 2014). Since these materials tend to be rich in calcium content and linked to CO_2 point source emissions, there is no need for mining and less raw materials are consumed. In addition to this, the chemical stability of these solid wastes is often lower than that of minerals that are extracted from the ground. (Huang *et al.,* 2023). Since alkaline-containing silicates, oxides, and hydroxides are the predominant reactive phase in carbonation of industrial solid waste, it is not necessary to separate reactive ions from the solid matrix (Jang *et al.,* 2023) 7–11% of all CO_2 emissions come from the aluminum and steel industries (Gunning, Hills, and Carey 2010). Environmental sustainability is being achieved by strict regulation of greenhouse gas emissions and responsible disposal of waste products from the steel industry. Within this context, it indicates that a combined approach to capturing CO_2 and enhancing the environmental and mechanical qualities of steelmaking slags is extremely desirable. As a result, carbonating industrial waste like aluminum dross and steel slag may be a promising strategy for reducing the CO_2 emissions at the steel mill (Gunning *et al.,* 2010; Xie *et al.,* 2022). Accelerated carbonation of steelmaking slags has been increasingly tested over the

past few years to evaluate the material's potential for CO_2 capture (Chang *et al.,* 2011; Gadikota, Utilisation, 2015; Pan *et al.,* 2014, 2012; Polettini, Pomi, and Stramazzo 2016; Alessandra Polettini *et al.,* 2016). The ability of various alkaline waters to sequester carbon dioxide is analyzed in **Table 1** and the structural diagram of carbonation of industrial wastes is illustrated in **Figure 1**.

Table 1. Illustration of alkaline solid waste found in literature.

Alkaline Solid Waste	Examples	Reference
Aluminum Dross	Smelting process	(Jones *et al.,* 2006)
Slag	Steelmaking slag, Blast furnace slag, Coal slag	(Alessandra Polettini *et al.,* 2016; Wang *et al.,* 2019; Yildirim and Prezzi 2011)
Fly ash	Municipal solid waste incineration (MSWI) fly ash, Coal fly ash, Oil shale ash	(Baena-Moreno *et al.,* 2022)
Air pollution control residue	Cyclone dust, Municipal solid waste incinerator	(Pan *et al.,* 2012)
The cement wastes	Cement/Concrete waste bypass dust of cement, Construction waste, Cement kiln dust, Blended hydraulic slag cement	(Gunning *et al.,* 2010; Wang *et al.,* 2019)
Mineral and mining processing wastes	Red mud (Bauxite), Asbestos tailings, Nickel tailings	(Baena-Moreno *et al.,* 2022)
Paper pulping and mill waste	Lime mud, Lime slaker grits, Green sludge dreg, Paper mill waste (calcium mud)	(Pöykiö and Nurmesniemi. 2008)
Sludge (incinerator) ash	Paper sludge incinerator ash, Sewage sludge incinerator ash, Steel wastewater sludge	(Baena-Moreno *et al.,* 2022)

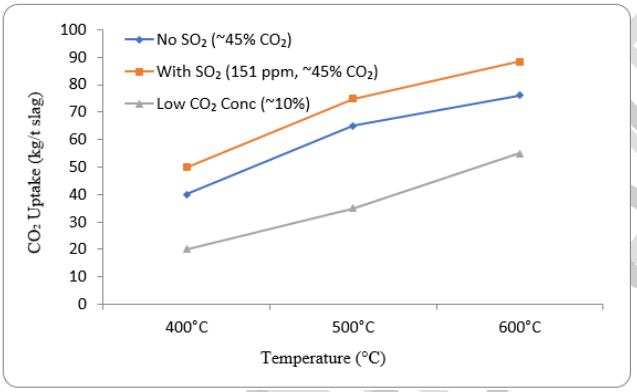


Figure 2. Gas–Solid Carbonation of SS under Different Temperature Conditions (Tien *et al.,* 2013; Pan *et al.,*, 2012; Lee *et al.,* 2023).

1.2.1. Steel slag for CO_2 sequestration

Steel Slag (SS) can be subdivided into a broad number of categories, such as Electric Arc Furnace Slag, Basic Oxygen Furnace Slag, Continuous Casting Slag, Argon Oxygen Decarburization Slag, and Ladle Furnace Slag, depending on the various stages of the smelting process (Ibrahim *et al.,* 2019). Free calcium oxide (CaO), dicalcium silicate ($2CaOSiO_2$), iron oxide (FeO/Fe_2O_3) and tricalcium silicates ($3CaOSiO_2$) are the primary components of steel slag. Around the world, 130 million tons of steel slag are produced every year, with the majority of it being disposed of in landfills, where it consumes precious farmland and pollutes the groundwater and soil (Mohammadian *et al.,*, 2015; Reddy *et al.,*, 2019; Xie *et al.,*, 2022). The high concentration of alkaline salts and CaO in steel slag gives it a significant carbonization activity, which enables the process to be carried out in the presence of water at temperatures and pressures that are comparable to those found naturally. Industrial alkaline solid wastes, such as calcium or magnesium oxide sources, are abundant and low-cost, making them ideal for CO_2 sequestration. As a result of the fact that these minerals have a naturally high calcium content and are commonly linked to CO_2 point source emissions, it is possible to use them without resorting to mining or needing the consumption of any extra raw materials. In addition, the chemical stability of these solid wastes tends to be poorer than the chemical stability of minerals that have a geological origin (He *et al.,* 2021; Siriwardena *et al.,* 2015).

Zhang *et al* investigated the carbonation of SS with flue gas under a variety of different operational settings. Temperature, CO_2 content, and the presence of sulfur dioxide are all parameters that can have an impact on the rate at which carbon is captured during the gas-solid carbonation of SS (Zhang *et al.,* 2020). The presence of sulfur dioxide (SO_2) helps increase the mineralization of carbon dioxide (CO_2) by silver sulfide (SS), particularly in the diffusion-controlled stage. This is most likely because SO_2 raises the surface activation energy of SS, which in turn makes it possible for more efficient CO_2 uptake. However, the limiting of gas diffusion had an effect on the maximum CO_2 sequestration that could be achieved, which was 88.5 kg CO_2 t^{-1}slag when the SO_2 concentration was 151 ppm. The chemical conversion rate of SS produced through direct aqueous carbonation is higher than that produced through SS produced through direct gas-solid carbonation. The dissolution of CO_2 in water is the first step in the three-step process by which SS and CO_2interact in aqueous solutions, followed by the release of Ca or Mg from SS and the subsequent precipitation of Ca or Mg carbonate (Pan *et al.,* 2012). The gas solid carbonation (CO_2 uptake capacity) by SS is shown in **Figure 2** for varying temperatures.

Nevertheless, if the CO_2 pressure reaches a particular level, the dissolution of SS becomes the limiting phase in the carbonation process (optimum CO_2 pressure of 3 bar and L/S to 0.4 mLg1 at ambient temperature; 13% wt CO_2 absorption) This occurs when the L/S ratio is lower than 0.4 mLg^{-1} (Wang *et al.,* 2021).The carbonation efficiency of SS (27%; real sequestration/theoretical sequestration capacity) does not significantly improve with pressure over the optimum range, but more energy is needed to maintain the same level of carbonation (Rushendra *et al.,* 2016). During the Ca/Mg extraction from SS, a porous layer is generated, which can hinder any further dissolving, as has already been described (Safari *et al.*,, 2009; Said *et al.*,, 2015). Additionally, the $CaCO_3$ products cover the reacting SS, preventing gas diffusion and the carbonation process (Zhao *et al.,* 2020). At 200 °C, 40% CO_2 concentration and 60% relative humidity, the carbonated shell of the BOFS was measured to be around 200 micrometers thick (Czaplicka *et al.,* 2020). It is commonly acknowledged that in order to obtain a rapid Ca/Mg dissolving rate from SS and a high conversion rate, you need to remove the "barrier layer" during the reaction (Polettini *et al.,* 2016; Reddy *et al.,* 2019; Sanna *et al.,* 2014).According to **Table 2**, the carbonation performance of steel slag is strongly governed by operating parameters and reactor configuration. A synthesis of the reported studies indicates that optimal carbonation efficiency is generally achieved at moderate temperatures (approximately 50–70 °C), liquid-to-solid ratios in the range of 10–20 mL g^{-1}, and CO_2 pressures below 5 bar. While elevated temperatures can enhance reaction kinetics, they simultaneously reduce CO_2 solubility in the aqueous phase, necessitating careful control of both temperature and water content during direct aqueous carbonation (Alessandra Polettini *et al.,* 2016; K. R. Reddy *et al.,* 2019; Ruschi *et al.,* 2020; Xie *et al.,* 2022). Moderate liquid-to-solid ratios facilitate effective leaching of Ca^{2+} and Mg^{2+} ions, whereas excessive water addition hinders CO_2 diffusion through the slurry and increases energy demand for mixing and downstream separation. In addition to process parameters, reactor design plays a critical role in determining carbonation efficiency. Intensified reactors, particularly rotating packed bed systems, consistently outperform conventional autoclave and slurry reactors due to enhanced gas–liquid–solid contact and shorter reaction times (Cui *et al.,* 2019; Alessandra Polettini *et al.,* 2016). Overall, the results demonstrate that balanced operating conditions combined with reactor intensification are more effective than increasing process severity for achieving high CO_2 uptake while maintaining acceptable energy efficiency in steel slag carbonation systems (Pan *et al.,* 2014).

Table 2. Comparison of carbonation efficiency of various SS types under varying conditions.

Material type	carbonation Method	Reactor	Solid comp	Gas/liquid phases	Operating conditions	Efficiency	References
EAFS	Aqueous	Autoclave reactor	CaO:32.9%,MgO:10%, (d = 38–106 µm)	15% vol CO_2, 85% vol N_2	L/S = 10 (mL/g), Q_L = 5 mL/min,*T* = 20 °C, *t* = 70 h	CO_2/100g slag, 1.5g	(Yildirim and Prezzi 2011)
BOFS	Aqueous	Rotating Packed Bed (RPB)	CaO:43.42%,MgO:9.15% (d < 62 µm)	100% vol. CO_2, (1.5kg/cm^2)	L/S = 20 (mL/g), Q_L = 1.2 L/min, QCO_2 = 2.5L/min, *T* = 65 °C, *t* = 30 min	CO_2/Kg slag 288 g	(Pan *et al.,* 2014)
EAFS	Accelerated	Rotating Packed Bed (RPB)	CaO:29.8%, MgO:6.4% (d < 150 µm)	100% vol. CO_2 (10 MPa)	L/S = 5 L/kg, *T* = 100 °C, *t* = 24 h	CO_2/kg slag, 260 g	(Pan *et al.,* 2012)
EAFS	Gas-solid	Stainless steel batch reactor	CaO:29.27%, MgO:7.88%, (d < 2 mm)	99.99% vol. CO2	T = 30 ± 2 °C, t = 3 h, CO_2 pressure= (3 bar)	CO_2/Kg, 12 g slag	(Saly *et al.,* 2018)
EAFS	Slurry	Stirred reactor	CaO:34.18%, MgO:8.44%, (d < 24.0 µm)	18.2% vol.CO_2, 4.0% O_2, 77.8% N_2	L/S = 10 (mL/g), *P* = 10.68 bar, *T* = 25 °C, *t* = 10 min	CO_2/kg slag, 52 g	(Saly *et al.,* 2018)
BOFS	Aqueous	Stainless steel reactor	Ca:32%, Mg:7.6%, (*d* = 63–100 µm)	40% vol. CO_2, (*P* = 5 bar)	L/S = 5 (mL/g), *T* = 50 °C, *t* = 4 h	CO_2/100g slag, 55 g	(Polettini *et al.,* 2016)

*EAFS, Electric Arc Furnace Slag and BOFS, Basic oxygen furnace slags.

1.2.2. Aluminum dross for CO_2 sequestration

Aluminum dross, a byproduct of the aluminum melting process, consists primarily of aluminum oxide (60-70%), with a smaller proportion of calcium oxide (8%), sodium chloride (nearly 15%), and potassium chloride (5-10%). Carbonation of aluminum dross typically occurs in less than 1 hour via the direct aqueous process method under low pressures and room temperature (Goswami, Shukla, and Singh 2022; Luo *et al.,* 2023; Zdeb *et al.,* 2023). So far, a few studies have been evaluated for CO_2 capture by Aluminum dross. Aluminum dross is generated in all the processes of molten aluminum, mainly including primary aluminum production (electrolytic aluminum), aluminum alloy production, scrap aluminum recycling and aluminum dross treatment process. In general, aluminum dross can be separated into primary aluminum dross and secondary aluminum dross based on the distinct types of aluminum that are contained within it. Primary aluminum dross is the byproduct of aluminum extraction; it is the gray-white dross that is skimmed off the top of the smelting furnace and is composed primarily of a mixture of metallic aluminum and aluminum oxide with an aluminum content of 15% to 70%. The primary ingredients are various forms of aluminum, including oxide, nitride, metal, salts, and others. Aluminum dross has a bulk density of 0.828-1.118 g/cm^3, an apparent density of 2.396-2.528 g/cm^3, and a pH of 9.03-10.14 in its leaching solution. Recent research has also been published on the topic of using aluminum dross as an affordable and effective adsorbent for the removal of lead, chromium, and arsenic from aqueous (Cui *et al.,* 2019), fluoride, cadmium, and zinc (Zhang *et al.,* 2017).These studies were carried out using aluminum dross. Additionally, the chemical composition of oxides and the alkaline nature of red mud may both contribute to the red mud's ability to generate very good material for the carbonation process, which is used to sequester carbon dioxide. The carbonation of alkaline material is a process that is both low-cost and risk-free, and it results in the production of goods that are thermodynamically stable. (Chang *et al.,* 2011). The utilization of carbonation may prove to be a beneficial solution to the challenges posed by the storage of aluminum dross and the annual emission of several thousand tons of carbon dioxide by aluminum manufacturers (Cui *et al.,* 2019; Jones *et al.,* 2006; Romero-Hermida *et al.,* 2017).

1.2.3. CO_2 Sequestration based on fly ash

During the process of burning coal, one of the waste products that is created is known as fly ash. The oxides of silicon, iron, aluminum, and calcium make up the bulk of fly ash. Other minor components include magnesium, potassium, and sodium. Potassium, magnesium, sodium, titanium, and sulfur are also present to a lesser degree. It is one of two types of ash that are collectively referred to as coal ash, and it is typically collected from the chimneys of coal-fired power plants (Lammers *et al.,* 2022; Mohammadian *et al.,* 2015). Ash can be used as a soil amendment and as a fertilizer. Bottom ash, which is the other sort of ash, is recovered from the bottom of coal furnaces after the coal has been burned. Fly ash is produced in enormous quantities in thermal power plants whenever significant quantities of coal are burned. To reduce the amount of damage done to the surrounding environment, fly ash should be used whenever this is feasible. According to investigations and experiments into its possible uses, fly ash has shown promise as an addition in the manufacturing of bricks, cement, and other construction materials (Zdeb *et al.,* 2023). Fly ash is a byproduct of the combustion of fossil fuels. After recently being impregnated with compounds that have a strong affinity for CO_2, activated carbons derived from fly ash have been researched for their potential as effective CO_2 sorbents. This was done in order to investigate their potential. In its natural state, fly ash can be utilized as a solid sorbent, although it is more commonly converted into porous materials with improved adsorption characteristics for greater utility. Fly ash can be used to create four different types of porous materials for CO_2 capture: activated carbons, mesoporous silica, alkali silicate, and zeolites (Xie *et al.,* 2022). To what extent synthetic porous materials can be used depends heavily on the chemical composition of fly ash. If the fly ash contains a high percentage of unburned carbon, it is converted into activated carbon with a greater surface area than the original fly ash. On the other hand, if the fly ash contains a low percentage of unburned carbon, it can be used to generate zeolites or mesoporous aluminosilicates. Activated carbon has a higher surface area than the original fly ash. Fly ashes that are high in aluminosilicate glass are preferred for use in the production of mesoporous silica and alkali silicates because it is relatively simple to extract the silicates from these ashes when the operating conditions are kept relatively benign. All commercial CO_2 capture systems have thus far employed chemical absorption techniques employing an aqueous alkanolamine solvent (e.g., Econamine FGSM, Kerr-McGee/ABB Lumus Crest MEA) Xie and coworkers Investigated fly ash derived activated carbon can remove up to 70% of CO_2 (Xie *et al.,* 2022).

1.2.4. Gypsum for CO_2 sequestration

Calcium accounts approximately 29.4% of gypsum, and sulfur accounts up 23.5% of it. Gypsum's molecular structure is typically represented as $CaSO_4{\cdot}2H_2O$, which indicates the presence of water. Although its chemical composition is inherently unstable, using waste gypsum produced during desulfurization as a component in carbon dioxide capture offers a number of advantages. It is cheap, readily available near power plants that produce large amounts of carbon dioxide, and has a fast reaction time when exposed to the gas (Wang *et al.,* 2019). Due to the high calcium sulfate dihydrate content of flue gas desulfurization gypsum waste, which is typically greater than 95 weight percent by weight (He *et al.,* 2021; Ruschi *et al.,* 2020; Wang *et al.,* 2021), it is an excellent source of residual calcium for the production of calcium carbonate by interaction with carbon dioxide (Romero-Hermida *et al.,* 2020). Due to the presence of this property, a great number of researches have been conducted to determine whether or not it is possible to precipitate calcium carbonate from

the gypsum waste that is generated during the process of flue gas desulfurization. Ruschi *et al.,* (2020) investigated which types of calcium carbonate can be created from the waste gypsum produced by flue gas desulfurization (Ruschi *et al.,* 2020).They discovered that vaterite and calcite co-precipitated during direct carbonation, while only calcite precipitated during indirect carbonation. Further investigation was prompted by the significant economic worth of vaterite, which can be attributed to its application in the pharmaceutical and textile industries. Most studies on carbonating gypsum waste from flue gas desulfurization have focused on the effects of different processing factors, such as temperature, flue gas flow rate, reaction duration, and liquid to solid ratio (Czaplicka *et al.,* 2020; Wang *et al.,* 2021). Claims have been made that carbon dioxide can be converted with an efficiency of 90-95% (Lee *et al.,* 2012a; Tan *et al.,* The time needed to complete a conversion is reduced when the temperature of the reaction is increased, as stated by Tan *et al.,* (2017). It also appears that a high liquid to solid ratio improves both the reaction stability and the final calcium carbonate quality. According to Tan *et al.,* (2017), raising a reaction's temperature accelerates the reaction, decreasing the amount of time required to accomplish the full conversion. It also appears that the reaction stability and final calcium carbonate quality are both enhanced by a high liquid to solid ratio. According to Lee *et al.,* (2012a), the utilization of a higher ammonia concentration (110-120%) improved both metrics.

The comparative assessment of CO_2 sequestration using industrial wastes—namely steel slag, aluminum dross, fly ash, and gypsum—reveals significant differences in performance, process requirements, and technological maturity. Among these materials, steel slag demonstrates the highest overall CO_2 sequestration potential due to its rich content of reactive calcium and magnesium oxides. These components enable efficient mineral carbonation, particularly under optimized aqueous conditions. However, despite its high uptake capacity, the process is often limited by diffusion barriers formed during carbonation, such as the development of $CaCO_3$ layers on particle surfaces, which hinder further reaction. In contrast, gypsum-based systems exhibit exceptionally high CO_2 conversion efficiencies (up to 90–95%), primarily through indirect carbonation routes involving calcium extraction and precipitation. While gypsum offers the advantage of producing high-purity and economically valuable calcium carbonate (e.g., calcite and vaterite), its dependence on additives such as ammonia and controlled reaction conditions introduces moderate process complexity.

Aluminum dross presents a distinct advantage in terms of reaction kinetics, as carbonation can occur rapidly (often within one hour) under ambient temperature and pressure conditions. This makes it an energy-efficient option; however, its relatively lower calcium content and heterogeneous composition limit its overall CO_2 sequestration capacity compared to steel slag. Additionally, the availability of aluminum dross is more constrained, which may restrict large-scale deployment. Fly ash, on the other hand, is abundantly available from coal-fired power plants and offers versatile pathways for CO_2 capture, including mineral carbonation and adsorption via derived materials such as activated carbon, zeolites, and mesoporous silica. Nevertheless, its performance is highly dependent on pre-treatment or activation processes, which increase both energy consumption and operational complexity. As a result, while fly ash-based systems are flexible, they are generally less efficient in direct CO_2 sequestration compared to calcium-rich wastes.

From an operational perspective, aluminum dross systems are the simplest to implement due to their mild reaction conditions, whereas steel slag and gypsum systems require more careful control of parameters such as temperature, pressure, liquid-to-solid ratio, and reactor configuration. Fly ash systems are the most complex due to the necessity for material modification prior to effective CO_2 capture. In terms of scalability, steel slag and fly ash stand out because of their large global production volumes, making them suitable for integration into industrial carbon capture strategies. Gypsum is also widely available, particularly in flue gas desulfurization units, although its long-term relevance may decline with the reduction of coal-based power generation in some regions.

Environmentally and economically, all four materials contribute to waste valorization and emissions reduction, but steel slag and gypsum offer the most compelling dual benefits. Steel slag enables large-scale CO_2 sequestration while stabilizing industrial waste, whereas gypsum carbonation produces high-value carbonate materials with applications in pharmaceuticals and construction. Overall, steel slag emerges as the most balanced and industrially viable option due to its high sequestration capacity and strong alignment with existing industrial processes. Gypsum follows closely due to its high conversion efficiency and product value, while fly ash and aluminum dross remain promising but comparatively less mature or efficient. These differences are also reflected in their technology readiness levels, with steel slag and gypsum nearing pilot-to-industrial deployment, whereas aluminum dross and fly ash technologies are still transitioning from laboratory to pilot-scale applications.

RPB reactors consistently outperform conventional slurry systems because centrifugal forces generate thin liquid films and intensified turbulence, substantially improving gas–liquid mass transfer coefficients and minimizing diffusion limitations. Although autoclave reactors achieve high carbonation conversion through elevated pressure and temperature, the associated heating and compression requirements significantly increase operational cost and life-cycle emissions. Slurry reactors offer easier scale-up and lower capital cost but generally suffer from lower carbonation efficiency due to weaker hydrodynamic mixing and slower CO_2 diffusion.

2. Parameters affecting the carbonation reaction

Many parameters, such as reaction temperature, reaction time, slag particle size, CO_2 pressure, solution pH, liquid-solid ratio, and others, affect the carbonation reaction of industrial solid wastes (Zhao *et al.,* 2020). The carbonation

reaction is highly sensitive to many different variables. Examining the variables are essential for attaining the maximum carbonation effect and optimizing the parameters (Rushendra Revathy *et al.,* 2016).

2.1. *Reaction time*

According to Xie *et al.,* (2022) and Yildirim and Prezzi (2011), the reaction of carbonation frequently immediately takes place in the beginning stage, and the degree of carbonation increases with the length of time that the reaction is allowed to progress until it is stopped (Xie *et al.,* 2022; Yildirim and Prezzi 2011). Only a marginal boost in carbonation is seen when the time of the reaction is allowed to continue beyond a certain point. Shrinking core metaphor is utilized rather frequently whenever an attempt is made to describe how carbonation works. Equation (3) provides a formalism for the reaction time (t) when the shrinking core model represents a condition in which Ca ion migration transition from the slag matrix to the liquid phase is the rate-limiting step in the process (Pöykiö *et al.,* 2008). The effective diffusion coefficient is indicated by the symbol De, and the number of moles of b ions (Ca ions) that can be found in one liter of aqueous phase A is indicated by the symbol CAB, which is measured in (mol/cm^3). A is the stoichiometric coefficient, B is the molar density of the slag, and rc is the radius of the un. A is the initial radius of the particles of industrial waste, and it is measured in centimeters. B is the molar density of the slag, and it is measured in milligrams per cubic centimeter. Equation 3 from Zhang *et al.,* (2015) study demonstrates that the amount of time required for a reaction grows in proportion to the square of the unreacted core radius. This demonstrates that the reaction time scales as the square of the unreacted core radius, which is in agreement with the findings (Zhang *et al.,* 2015).

$$t = \frac{\rho_B R^2}{6BD_e C_{AB}}\left[1 - 3\left(\frac{r_c}{R}\right)^2 + 2\left(\frac{r_c}{R}\right)^3\right] \quad (8)$$

As a result, the initial carbonation reaction requires a shorter time to reach a given level since the unreacted core radius is larger. Carbonation processes reach their highest rate when the unreacted core radius is at its smallest. Changes in carbonation growth rate are indicated by data from Chang *et al.,* (2011) and Pan *et al.,* (2016) and were also noted by Huijgen *et al.,* (2005), after 20 minutes. Within the first 10 minutes of the reaction, the carbonation level increases dramatically. Autoclaves and RPBs are used by both Huijgen *et al.,* (2005) and Pan *et al.,* (2014), which undoubtedly accelerates the mass transfer of ions and the development of the reaction, but also clarifies the disparity in the research' estimates of the point at which carbonation levels stabilize (Huijgen *et al.,*, 2005; Pan *et al.,*, 2014). In the slurry reactor employed by Chang *et al.,* (2011) and Pan *et al.,* (2016), the reaction stabilized at a slower rate. The first stage of the carbonation reaction often proceeds quickly under these conditions (Chang *et al.,* 2011; Pan *et al.,* 2016).

2.2. *Reaction temperature*

The carbonation reaction is sensitive to changes in temperature in complex ways. According to research, the reaction system's physical properties are modified by temperature, either directly or indirectly, through evaporation, viscosity changes, or diffusion rates (Lee *et al.,* 2016). According to Ruschi and colleagues (Ruschi *et al.,* 2020), there is a connection between temperature and the rate constants as well as the thermodynamic constants of the carbonation precipitation process. This connection also exists between the dissolving of CO_2 and the dissolution of minerals. According to (Kim *et al.,* 2023), a rise in temperature makes it easier for calcium ions to be leached out of the slag matrix. This is because the effective coefficient diffusion of calcium ions in the slag matrix can be increased when the temperature is raised. Teir *et al.,* (2016) steel slag leached in acetic acid at 30°, 50°, and 70° C. They found that the ratio of Ca ions leached at 30 degrees Celsius was much lower than the ratio of Ca ions leached at 50 degrees Celsius. Even while the leaching ratio was greater at 70 degrees Celsius than it was at 50 degrees Celsius, it was still lower at 70 degrees Celsius. According to Teir *et al.,* (2016), the fact that the leaching reaction is exothermic is what causes this behavior (Teir *et al.,* 2016).

A decreased concentration of CO_3^{-2} ions in the aqueous phase, as a result of an increase in temperature, limits the precipitation reaction of carbonation. The level of carbonation produced by the direct carbonation process depends on the temperature at which it takes place. Research by (Huang *et al.,* 2023; Pan *et al.,* 2012; Quan *et al.,* 2023); shows that the carbonation degree is highest between 50 and 60 degrees Celsius, and that raising the temperature over this point causes the carbonation degree to decrease. Based on their findings, Huang *et al.,* (2023) have determined that this crucial temperature lies at 200 °C. Because different reactions call for distinct kinds of reactors, the optimal temperature tends to shift accordingly. Since the decrease in CO_2 solubility caused by temperature can be counteracted by excessive pressure, elevated temperature has a positive influence on carbonation over a broad temperature range. This is because the loss in CO_2 solubility due to an increase in temperature can be counteracted by maintaining a high enough pressure. Changes in temperature have a stronger influence on the morphology and structure of carbonate minerals. For instance, Czaplicka and coworkers (Czaplicka *et al.,* 2020) found that vaterite and calcite formed more frequently at low temperatures (14-30 °C) when the pH was greater than 10, but aragonite formed more frequently at high temperatures (60-80 °C) under the same conditions. The conclusions were bolstered by the experimental findings of Chang *et al.,* (2011). Above 25 °C, vaterite and calcite predominate as the most prevalent $CaCO_3$ forms, but above 80 °C, aragonite predominates. An increase in temperature has been shown to hasten the leaching reaction. However, since the leaching reaction is exothermic, increasing the temperature may increase the leaching ratio if the promotion effect of the higher temperature outweighs the inhibition effect of the

exothermic reaction. It has been shown that the degree of carbonation for direct carbonation increases when the temperature's inhibitory effect on CO_2 dissolving is smaller than its stimulating effect on the leaching process, and vice versa (Chang *et al.,* 2011).

2.3. *CO_2 pressure and stirring rate*

The carbonation reaction can be sped up in theory by increasing the CO_2 pressure, as more CO_2 will be dissolved in the water. On the other hand, this will only be the case if the CO_2 mass transfer is the stage in the carbonation process that is responsible for influencing the rate of carbonation process (Chang *et al.,* 2011; Pérez-Moreno *et al.,* 2014). Because of this, the effect of CO_2 pressure on the amount of carbonation is not linear. However, the level of carbonation does react to an increase in CO_2 pressure when it is below this threshold. If the limit is exceeded, the contribution that it makes to the overall level of carbonation will be rendered insignificant (Alessandra Polettini *et al.,* 2016). Various researchers have arrived at contrasting findings about this dividing line. He *et al.,* (2021) discovered that this threshold is 9 bars via their research, however Goswami *et al.,* (2019) discovered that it is 5 bar through their research. Baena-Moreno *et al.,* (2022) were able to determine a range of thresholds by using a variety of experimental conditions (Baena-Moreno *et al.,* 2022; Goswami, Shukla, and Singh 2022; He *et al.,* 2021). They discovered that the threshold pressure at a temperature of 50 degrees Celsius is 4 bar, but that the threshold pressure at a temperature of 100 degrees Celsius is just 2 bar. It has been demonstrated that the threshold has a dynamic range of values under a variety of experimental conditions. According to Polettini *et al.*,, if the CO_2 pressure is increased above this limit, the degree of carbonation of the slag matrix will decrease, and the carbonation process will come to a complete and grinding end. It is possible that this is the case; however, neither Huijgen *et al.,* (2005) nor Omale *et al.,* (2019) discovered any evidence of this in their respective research. According to Pollettini *et al.,* (2016), additional research is required to determine the extent to which carbonation is affected by a rise in CO_2 pressure that is greater than the threshold (Polettini *et al.,* 2016). Increasing the reaction rate allows for a more rapid diffusion of Ca ions from the slag matrix into the solution and a more rapid mass transfer of CO_2 from the gaseous to liquid phases (Saly *et al.,* 2018). How well a solution is mixed depends in part on how fast it is stirred. Huijgen *et al.,* (2005) found that the carbonation level in a combination was significantly affected by the stirring rate when it was less than 500 revolutions per minute. This is because the CO_2diffusion rate was inadequate since the slurry was not mixed well enough below this level. Once this threshold was passed, further increases in stirring speed had only a little effect on the resulting carbonation. To provide a more general explanation, a higher partial pressure makes it easier for CO_2 to dissolve, which results in a bigger contribution of CO_3^{-2} ions to the process and a higher degree of carbonation. When the stirring rate falls below a specific threshold, usually 500 revolutions per minute, increasing the pace will create a significant increase in the amount of carbonation that is present. If this number is exceeded, however, raising the stirring rate further will not appreciably alter the degree of carbonation (Alessandra Polettini *et al.,* 2016). This is because the ion mass transfer stage of the reaction is no longer a rate determining stage after it has been reached.

2.4. *Particle size of slag*

Slag's specific surface area can be increased by making the slag particles smaller, so exposing more of the slag's interior to the aqueous phase. Furthermore, particle size may shorten the time it takes for ions to diffuse from the slag's matrix to the surface. Nonetheless, slags of varying particle sizes exhibit a wide range of chemical compositions; for example, finer-grained slags likely to have higher Mg and Ca ion concentrations, that can be explained by the grindability of the various mineral phases that make up the slag. Calcium is more concentrated in finely ground slag because the free CaO, $Ca(OH)_2$, and calcium silicate mineral phases are more amenable to grinding than calcium ferrite or iron aluminate. Carbonation degree increased from 24% to 74% when particle size was decreased from <2 mm to <38 µm, as demonstrated by the power function relationship between carbonation degree and particle size with a power that ranges between 0.7 and 0.4 depending on the temperature (Romero-Hermida *et al.,* 2017). In an experiment that was carried out by (Goswami *et al.,* 2022), it was demonstrated that the concentration of calcium ions in the steel slag increased from 189 to 584 ppm after 30 minutes of reaction when the particle size of the steel slag was decreased from 2–3.5 mm to 0.5 mm. This was the result of the reduction in the steel slag particle size. Meng and colleagues (Meng *et al.,* 2022) found that BOF slags of varying particle sizes had notably dissimilar CaO concentrations. Slags with a particle size of 840-1190µm had a CaO content of 43.59%, slags with a particle size of 500-840 µm had a CaO content of 45.39%, and slags with a particle size of 350-500 µm had a CaO content of 46.49%. CaO content was 48.16 percent at a particle size of 125 nm or less, and these numbers corroborated the general trend of rising Ca content with decreasing particle size. In conclusion, there are two ways in which particle size reduction might speed up a reaction; nevertheless, smaller particles require more grinding time, which increases the energy required for the reaction. A good slag particle size can be chosen by striking a balance between the energy required for the process and the carbonation degree, which is important in industrial applications of mineral carbonation (Chang *et al.,* 2011; Czaplicka *et al.,* 2020).

2.5. *Liquid solid ratio*

According to Saly *et al.,* (2018), the presence of water in the aqueous phase of the carbonation reaction system has an effect not only on the consumption and dissolution of the slag, but also on the diffusion of ions and the mixing conditions of the slag-water slurry phase. When the liquid-to-solid ratio is low, the ionic strength of the aqueous phase can increase due to the importance of water in this system (Galina *et al.,* 2019). The slurry's high alkalinity and low liquid-to-solid ratio are both caused by the high

concentration of slag, which contributes to the slurry. According to research done by K. R. Reddy and colleagues in 2019, a high-pH environment has a high pH buffering capacity, which allows the carbonation reaction to proceed at a faster rate. On the other hand, if the ratio of liquid to solid is too low, the reaction slurry will not be able to be stirred effectively. As a consequence of this, both the rate of Ca ion leaching from solids and the rate at which CO_2 is dissolved in water slow down (Goswami *et al.*,, 2022). Experiments carried out by Veetil *et al.,* 2020 demonstrate that the carbonation degree of slag is approximately 3% when the liquid-solid ratio is equal to zero, which indicates that there is no water present in the mixture. Nevertheless, when the ratio is increased to 10:1, this percentage rises to 18.3%. When there is a ratio of liquid to solid that is 20 to 1, the level of carbonation is at its highest point; after that, it begins to gradually drop. They came up with the theory that since an excessive liquid-to-solid ratio acted as a barrier to the transfer of mass and decreased the ionic strength, the carbonation reaction was significantly slowed down as a result. If there is a greater proportion of liquid to solid, more carbon dioxide and calcium ions will dissolve in the water; nevertheless, the effect of carbonation will be lessened if there is an excessive amount of water added. At the moment, water serves as a mass transfer barrier, preventing carbon dioxide from diffusing into the liquid coating that is present on the surface of the slag (Polettini *et al.*,, 2016). According to (Chang *et al.*,, 2011; Rushendra Revathy *et al.*,, 2016) the process of carbonation is more expensive since a larger reactor is necessary to facilitate the reaction with an excessive amount of water. According to Saly *et al.,* (2018), the presence of water in the aqueous state of the carbonation reaction system has an effect not only on the hydration and dissolution of the slag, but also on the dispersion of ions and the conditions under which the slag-water slurry is mixed. This has an effect not only on the hydration and dissolution of the slag, but also on the conditions under which the slag is mixed with the water. The ionic strength of the aqueous phase can increase when the liquid-to-solid ratio is low (Galina *et al.,* 2019). Water is a crucial component of this system. The slurry has a high alkaline content as a consequence of the presence of a considerable quantity of slag, which can be deduced from the low liquid-to-solid ratio that exists within the mixture. According to research done by K. R. Reddy and colleagues in 2019, a high-pH environment has a high pH buffering capacity, which makes it possible for the carbonation reaction to continue more quickly. Carbonation degrees of slag vary from roughly 3% at a liquid-solid ratio of 0 (without water) to 18.3% at a ratio of 10:1 (Veetil *et al.,* 2020). The level of carbonation did not appreciably increase even after the liquid-to-solid ratio was increased to its greatest possible degree. The level of carbonation is at its peak when the liquid-to-solid ratio is 20:1; after that point, it begins a slow decline until it reaches its lowest point. They concluded that the rate of the carbonation process was slowed down to some extent because an excessively high liquid-solid ratio operated as a barrier to the transfer of mass and decreased the ionic strength. In general, increasing the liquid-solid ratio assists in the dissolution of additional carbon dioxide and calcium ions in the water; however, adding an excessive amount of water dampens the effect of carbonation. According to Pollettini *et al.,* (2016), water acts as a mass transfer barrier that stops CO_2 from diffusing into the liquid coating that is on the surface of the slag. However, the cost of carbonation goes up because a larger reactor is required to assist the reaction with a significant quantity of water (Chang *et al.*, 2011; Rushendra Revathy *et al.,* 2016).

2.6. *pH*

One additional key factor in the carbonation reaction is the pH of the solution. The carbonation process significantly reduces the alkalinity of steel slag (Mohammadian *et al.*,, 2015; Pöykiö and Nurmesniemi 2008; Saly *et al.*,, 2018). Large amounts of highly reactive free CaO can be found in BOF slag and EAF slag, and they can be dissolved in water to produce $Ca(OH)_2$ ((Romero-Hermida *et al.*,, 2020). As a result, the pH of the new steel slag leaching solution is normally larger than 12, but after being subjected to carbonation, it falls to a value that is greater than 7 points below 7. Carbonation, or the conversion of carbonic acid into hydrogen ions, is commonly used to reduce the alkalinity of steel slag as a buffer (Pan *et al.*,, 2014).The leaching response benefits from a low pH, although carbonate precipitation is hampered. In order to achieve a happy medium between the active metals' solubility in CO_2 and the precipitation of the carbonates, it is clear that the pH of the solution must be carefully controlled during mineral carbonation. The Bjerrum plot for the carbonate system reveals that the species generated by CO_2 in water take on different forms depending on the pH value: at higher pH levels, CO_3^{-2} ions predominate, whereas at lower values, bicarbonate ions do (Li, Ling, and Pan 2022).

3. Challenges of large-scale implementation

A considerable amount of research has been carried out in laboratory settings on the interaction between carbon dioxide and diverse solid wastes generated from industrial environments. Notwithstanding, the industrial implementation of the process remains a distant prospect, owing to the numerous impediments that must be surmounted. These impediments encompass the heterogeneity of the initial mineralogical composition of solid waste, limitations in reaction kinetics, escalation in energy and economic costs, and the simultaneous enhancement of process parameters and mitigation of environmental impacts.

3.1. *Environmental impact and energy input requirements*

Crushing, grinding, and sifting the material to increase the reaction rate is an electrically-intensive process that is necessary for both direct and indirect carbonation (Ruschi *et al.,* 2020; Wang *et al.,* 2021). According to the findings of an analysis, SS direct aqueous carbonation requires between 980 and 6,300 MJ t^{-1} CO_2 while the method of indirect carbonation of SS requires between 244 and 427 kWh t^{-1} CO_2, heating, CO_2 compression, and solid/liquid separation require energy (Ruschi *et al.,* 2020). It is essential to conduct an in-depth analysis of the relationship which emerges between the amount of energy that must

be put into the production of PCC products and the benefits such products provide (as well as their market worth). In addition, carbonized slag and residual slag require additional research into their treatment and potential applications. along with the short-term and long-term leaching behaviors of carbonated slag, as well as the possible dangers to the environment need to be assessed (Li *et al.,* 2022; K. Reddy *et al.,* 2019).

3.2. *Cost of implementation*

The high cost of CCS technology is one of the most major obstacles that prevents widespread adoption of these technologies. The estimates of how much it will cost vary greatly, but the most common factors are the equipment and energy required for the capture and compression stages. Collecting the CO_2 can reduce the efficiency of power and industrial units and increase water use, which can add additional expenditures that could make the project unfeasible. Furthermore, due to the novelty of CCS deployment, financial returns on a CCS project are riskier than conventional operations. The private cost of the investment rises even further as a result of investors demanding larger risk premiums (the minimum amount of expected return required to attract investment). Consequently, reducing investors' exposure to risk is critical for encouraging their participation in CCS investment and development. Policies in the areas of research, development, and deployment (RDD) that reduce the uncertainty surrounding these types of expenditures are, of course, highly needed (Mohammadian *et al.,* 2015; Ruschi *et al.,* 2020).

3.3. *Transportation challenges*

In addition to the high costs associated with the technology required for capture, there are major issues associated with transferring captured carbon dioxide once it has been stored. It takes a significant amount of energy to compress and cool CO_2 before sending it via pipes, where it must be maintained at high pressure and low temperatures. Additionally, the construction of pipelines is a costly task. Because the already-existing pipelines for oil and gas cannot be employed to carry the highly pressurized and compressed CO_2, it will be necessary to construct new pipelines. Any impurities in the stream, including water, have the potential to cause pipeline damage, major leaks, and even explosions when compressed carbon dioxide rapidly expands to a gas. Pipes and other pieces of equipment can become brittle when subjected to temperatures that are extremely low. Third, carbon capture and storage can be more difficult and expensive to implement in places that are geographically distant from geological formations that are suitable for use as storage sites. This is due to the fact that each CO_2 source needs to be connected to an appropriate storage site via pipeline (Sanna *et al.,* 2014).

4. Potential applications of calcium carbonate production from industrial wastes

The synthesis of ultrafine $CaCO_3$ via CO_2 mineralisation using industrial solid wastes offers a viable approach for reducing CO_2 emissions. Despite considerable advancements in laboratory-scale research, the shift to pilot and commercial-scale applications has been constrained. In 2014, Finland initiated a pilot plant to convert steel slag and CO_2 into PCC. This batch-mode facility processed a maximum of 20 kg of steel slag and 190 L of NH_4Cl solvent each cycle, resulting in an approximate yield of 10 kg of PCC. The leaching phase attained an 80% efficiency with a 1 mol L^{-1} NH_4Cl solution, but the carbonation phase obtained a 71% efficiency, yielding high-purity PCC (99.5%). The effectiveness of NH_4Cl solvent recycling for calcium leaching diminished after ten cycles, indicating a necessity for more optimization. Park *et al.,* (2023), made additional contributions to pilot-scale developments by creating a reactor that can generate 20 kg of $CaCO_3$ daily. The procedure employed 0.5 mol L^{-1} HCl for calcium extraction from waste concrete, thereafter adjusting the pH with NaOH to eliminate contaminants. The introduction of CO_2 into the system resulted in a production efficiency of 96% $CaCO_3$ in 30 minutes, yielding a final calcium purity of 99%. A further instance involves a pilot-scale facility established by Iizuka *et al.,*, aimed at processing concrete sludge and generating $CaCO_3$. This procedure entailed the extraction of calcium through water to hydrate unreacted cement and produce a calcium-enriched slurry. Following filtration, the liquid was reacted with CO_2-saturated flue gas to yield high-purity $CaCO_3$ (>97%). During a week, the facility processed 356.7 tonnes of concrete sludge, sequestering 0.140 tonnes of CO_2 and attaining a net decrease in CO_2 emissions of 118 kg. This illustrates the viability of extensive CO_2 sequestration at conventional temperature and pressure without requiring CO_2 purification or pressurization. Xie *et al.,* (2022)

P, presented a novel method for transforming phosphor-gypsum (PG) into $CaCO_3$ and $(NH_4)_2SO_4$ via CO_2 mineralization via a pilot-scale apparatus. Cooling flue gas to 50 °C and treating it with ammonia decreased the CO_2 concentration from 15% to 4.5%. The processed liquid underwent mineralisation with PG, attaining a 90% conversion rate at 75 °C over six hours. This process generated granular $(NH_4)_2SO_4$ fertilizer, yielding an anticipated income of $17 USD per tonne of CO_2 processed. Notwithstanding these advancements, the extensive application of industrial waste for $CaCO_3$ synthesis encounters considerable obstacles. These encompass elevated energy requirements, diminished carbonation efficiency, significant expenses, challenges in regulating crystal shape, and attaining high product purity. Overcoming these challenges necessitates ongoing refinement of process parameters and the creation of economical, efficient technologies to improve economic and environmental sustainability.

4.1. *Life cycle assessment in carbon capture and storage by carbonation*

The life cycle assessment LCA, is a useful instrument for determining the effects on the surrounding ecosystem and

the amount of resources that are used during the entirety of a product's or process's full production cycle (Chang *et al.,* 2011). The carbonation of industrial waste uses up energy and materials, and it also leads in the release of carbon dioxide (CO_2) during the process; as a consequence, it is necessary to conduct an in-depth analysis of the procedure utilizing Life Cycle Assessment (LCA) (Ruschi *et al.,* 2020).The authors Li *et al.,* (2014) utilized the Umberto 5.5.4 program to perform out a Life Cycle Assessment (LCA) and carry out an in-depth examination of the CO_2 fixation that was brought about by the carbonation of steel slag and iron. In the first three, an autoclave, slurry reactor, and RPB were used for direct carbonation, whereas in the latter three, ammonium nitrate, ammonium chloride and acetic acid were used as extractants for indirect carbonation. According to the findings, while considering the Global Warming Potential (GWP), the effect on GWP that is brought about by indirect carbonation is frequently lower than that which is brought about by direct carbonation. This is the case regardless of the kind of carbonation. The slag carbonation procedure that makes use of an autoclave exhibits the largest additional CO_2 emissions when it comes to direct carbonation. This is due to the fact that heating and pressurizing need a significant amount of the available electrical energy. The RPB demonstrated a rapid reaction rate; nevertheless, the amount of carbonation produced by the slurry reactor (scenario 2) was significantly less than that produced by either of the other two scenarios. It was proposed to combine the slurry reactor and the RPB in order to maximize the amount of carbonation achieved while minimizing both the impact on the environment and the additional CO_2 emissions. When it comes to the process of indirect carbonation, ammonium nitrate and chloride both have a lower global warming potential (GWP) than acetic acid does. As a consequence of this, ammonium salt is an excellent choice for an extractant when it comes to the process of indirect carbonation (Li *et al.,* 2022).

5. Integration of Industrial CO_2 Sources and Waste Streams and challenges for scale up

Industrial Industrial symbiosis represents a promising strategy for integrating CO_2-emitting industries with waste-generating sectors (Ghouleh *et al.,* 2017; Pan *et al.,* 2012). In integrated steel plants, flue gas streams containing 10–20% CO_2 can be directly coupled with steel slag carbonation systems, thereby minimizing transportation requirements and reducing emissions associated with CO_2 purification and compression (Huijgen & Comans, 2005; Pan *et al.,* 2012). Similarly, flue gas desulfurization gypsum generated in coal-fired power plants can be converted into precipitated calcium carbonate (PCC) while simultaneously producing ammonium sulfate fertilizer (Yadav *et al.,* 2019; Ukwattage *et al.*, 2015).

Pilot-scale demonstrations further highlight the feasibility of integrated carbonation systems. In Finland, a pilot-scale steel slag carbonation process using NH_4Cl extractant achieved approximately 71% carbonation efficiency and produced high-purity PCC (~99.5%) (Said *et al.,* 2013; Eloneva *et al.,* 2010). Another pilot-scale system converted phosphogypsum into $CaCO_3$ and ammonium sulfate while treating industrial flue gas streams (Ukwattage *et al.,* 2015). These integrated systems support circular carbon management by coupling waste utilization, CO_2 sequestration, wastewater reuse, and resource recovery within a single industrial framework (Kirchofer *et al.*, 2013; Pan *et al.*, 2015).

Despite significant laboratory-scale advancements, industrial implementation of mineral carbonation remains technically challenging (Lackner, 2003; Sanna *et al.,* 2014). Heat management is a major limitation because carbonation reactions are exothermic, and inadequate thermal regulation can reduce carbonation kinetics and create reactor instability during large-scale operation (Sanna *et al.,* 2014). Slurry-based systems also experience mixing constraints due to high solid loading, which may result in sedimentation, non-uniform gas distribution, and reduced gas–liquid interfacial area (Huijgen *et al.*, 2005; Bobicki *et al.,* 2012).

Reactor sizing presents additional engineering challenges. Increasing reactor dimensions often reduces gas–liquid contact efficiency and increases residence time requirements, thereby decreasing overall productivity (O'Connor *et al.,* 2005). Large-scale systems also require substantial energy for slurry circulation, CO_2 compression, and solids handling (Lackner, 2003; Sanna *et al.,* 2014). Consequently, future scale-up strategies should prioritize modular reactor design, intensified hydrodynamics, and heat integration approaches to improve process feasibility and energy efficiency (Bobicki *et al.,* 2012; Pan *et al.,* 2015).

6. Impact of flue gas composition on carbonation efficiency

The composition of industrial flue gas significantly influences carbonation performance (Santos *et al.,* 2013; Huijgen & Comans, 2006). Sulfur oxides (SO_x) may react with alkaline phases to form sulfates, thereby competing with carbonate formation and reducing effective CO_2 uptake (Huijgen & Comans, 2006). However, low concentrations of SO_2 have also been reported to increase surface activation of steel slag and enhance initial carbonation kinetics (Santos *et al.,* 2013). Nitrogen oxides (NO_x) can alter solution chemistry and affect pH-dependent dissolution processes, although their overall effect on carbonation remains insufficiently understood (Bobicki *et al.,* 2012).

Moisture content also plays a dual role in carbonation systems. Moderate humidity enhances CO_2 dissolution and ion mobility, thereby promoting carbonate precipitation (Pan *et al.,* 2012). Excessive moisture, however, may hinder gas diffusion and increase slurry handling requirements (Sanna *et al.*, 2014). These findings indicate that variability in flue gas composition necessitates careful pretreatment and process optimization to ensure stable carbonation performance under industrial operating conditions (Huijgen *et al.,* 2005; Santos *et al.,* 2013).

7. Conclusion and future prospects

Mineral carbonation using industrial solid wastes has advanced significantly in recent years, driven by

innovations in reactor design, chemical extractants, process optimization, and enhancement treatments. A comparative evaluation of major feedstocks reveals clear performance distinctions: steel slag exhibits the highest CO_2 sequestration capacity (up to ~260–288 kg CO_2 per ton of slag), while gypsum-based systems achieve the highest conversion efficiencies (90–95%) under optimized conditions. Fly ash-derived sorbents can remove up to ~70% of CO_2 following activation, whereas aluminum dross enables rapid carbonation (<1 hour) under ambient conditions, albeit with comparatively lower overall capacity. Although the use of industrial wastes significantly reduces raw material costs, overall process economics remain dependent on reactor configuration and operating conditions, with intensified systems offering higher efficiency at the expense of increased capital and energy inputs. These findings highlight that improvements in carbonation efficiency are often accompanied by trade-offs, including higher energy consumption, operational costs, and potential process-related CO_2 emissions.

For iron- and steel-slag-based systems, a synthesis of the reviewed studies confirms that aqueous carbonation routes consistently outperform gas–solid pathways due to enhanced ion dissolution and improved gas–liquid–solid mass transfer. Reactor intensification strategies, such as rotating packed bed and other high-shear systems, enable rapid CO_2 uptake within significantly reduced reaction times. Optimal carbonation performance is generally achieved under moderate operating conditions (50–70°C, CO_2 pressure <5 bar, and liquid-to-solid ratio of 10–20 mL g^{-1}). Increasing temperature, pressure, or water content beyond these ranges results in only marginal improvements in carbonation efficiency while substantially increasing energy demand associated with CO_2 compression, heating, slurry handling, and downstream separation. This demonstrates that balanced operating conditions combined with reactor intensification are more effective than aggressive process severity in achieving high CO_2 uptake with acceptable energy efficiency.

Despite these advancements, several critical technological challenges remain. Energy intensity associated with process intensification and CO_2 compression continues to limit large-scale feasibility. Reaction kinetics are often constrained by diffusion limitations and the formation of passivation layers, particularly in steel slag systems where carbonate coatings inhibit further Ca/Mg dissolution. Additionally, process scalability remains a major barrier, as laboratory-optimized systems do not always translate effectively to industrial-scale operations due to mass transfer limitations and feedstock heterogeneity. In systems such as fly ash, the need for pre-treatment or activation further increases process complexity and energy demand.

Indirect carbonation pathways, particularly those leading to precipitated calcium carbonate (PCC) production, represent a highly promising approach for coupling CO_2 sequestration with economic value generation. Under controlled conditions, PCC can be produced with high purity and significant commercial value. Moreover, mineral carbonation of industrial wastes, especially steel slag, enables the recovery of valuable metals such as aluminum, iron, and titanium, with several studies reporting commercially viable recovery rates and product purities. These integrated approaches significantly enhance the overall techno-economic feasibility of carbonation processes.

Future research should prioritize resource-efficient and integrated process innovations. The use of industrial wastewater as a reaction medium offers a dual benefit of reducing freshwater consumption and enabling the co-treatment of gaseous, liquid, and solid waste streams. However, the complex ionic composition of such wastewater introduces uncertainties in carbonation mechanisms, which remain insufficiently understood and require systematic investigation. In addition, recycling of the aqueous phase after carbonation presents a valuable opportunity to improve process sustainability by retaining reactive species, reducing operational costs, and promoting multi-cycle CO_2 mineralization. To bridge the gap between laboratory research and real-world implementation, pilot-scale validation and industrial integration studies are essential. The development of hybrid systems combining carbonation with resource recovery and carbon valorization pathways will be critical for achieving both environmental and economic sustainability.

In conclusion, mineral carbonation of industrial solid wastes represents a highly promising pathway for carbon capture and utilization within a circular economy framework. However, its large-scale deployment will depend on achieving an optimal balance between carbon sequestration efficiency, energy consumption, and economic viability, supported by continued interdisciplinary research, industrial collaboration, and enabling policy frameworks.

Highlight

- This review focuses on the application of metallurgical waste for CO_2 mineralization
- CO_2 mineralization performance of aluminum dross, steel slag, fly ash and gypsum was reviewed.
- The effects of various influencing factors including temperature, pressure, particle size, contact duration and mixing ratio were complied.
- Recommendations for future research and commercialization of the technology were also proposed.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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