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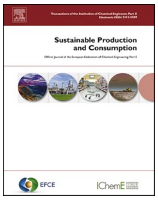

Review Article

Dual adoption opportunities and prospects for mining and industrial waste recovery through an integrated carbon capture, utilization and storage

Faradiella Mohd Kusin [a,b,*], Sharifah Nur Munirah Syed Hasan [a], Verma Loretta M. Molahid [a], Muhammad Hameer Soomro [a]

[a] Department of Environment, Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[b] Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

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ABSTRACT

Mining waste is globally available in abundance and can be seen as a useful mineral resource for long-term carbon capture which can be turned into revenue-generating products. This review highlights a new concept for mining waste utilization through an integrated carbon capture, utilization and storage (CCUS) technology in response to the long-term target for net-zero emissions. A framework for mining waste utilization by means of CCUS is introduced through integration of accelerated mineral carbonation and carbonation curing technologies. Potential CO_2 sequestration of mining waste is mainly attributable to the availability of Ca-, Mg- and Fe-based silicate and oxide minerals and manipulation of process variables. It was estimated that the current rate of carbonation efficiency of mining waste through direct and indirect mineral carbonation is about 11 % and 55 %, respectively, while CO_2 capture capacity through carbonation curing is about 20.6 %. It can be projected that with the current rate of CO_2 sequestration, this accounts for about 21.1–100 % of the net-zero target by 2035 via CCUS. The combined mineral carbonation and carbonation curing might offset 33.4–100 % of CO_2 emissions from the mining industry and 15.4–60.9 % of the net-zero target by 2050. Despite technical, economic and environmental challenges, the framework provides pathways for a sustainable mining waste recovery to meet the 2050 net-zero emissions target.

1. Introduction

Carbon dioxide, CO_2 accounts for about three quarters, i.e. ~74 % of the total greenhouse gas (GHG) emissions globally. The United Nations Emissions Gap Report 2022 finds that there is an urgent need for global-wide rapid transformation to cut 45 % of emissions by 2030 to be on track in limiting global warming to 1.5 °C (UNEP, 2022). The global GHG emissions by sectors indicate that the energy sector contributes about 73 % of the emissions through energy use in industry, transport and energy use in buildings. The Intergovernmental Panel on Climate Change (IPCC) proposes that industrial emissions of CO_2 can be reduced in limiting global warming to 1.5 °C which can be achieved from a technological carbon reduction perspective including carbon capture, utilization and storage (CCUS) (IPCC, 2018). CCUS technologies play an important role in meeting the global targets for energy reduction on its path to net zero and are identified as one of the major categories of technology-rich and energy-intensive sub-sector industry models in the International Energy Agency (IEA) Global Energy and Climate Model (IEA, 2022). The IEA Net Zero by 2050 Scenario highlights the need for an accelerated deployment of CCUS to meet the net-zero targets in 2050 (IEA, 2021a). The scenario projects that about 4 Gt of CO_2 will be captured in 2035, which is almost a 100-fold increase from current capacity, and to nearly 200 times higher in 2050 reaching 7.6 Gt of CO_2 being captured, transported and used or stored. The IEA Legal and Regulatory Framework for CCUS identifies CCUS as the group of technologies that can contribute to deep emission reductions in key heavy industry sectors, i.e. cement, steel and chemicals production, while supporting CO_2 removal from the atmosphere (IEA, 2022). Nearly 60 % of energy consumption in the industrial sector originates from these three major industries that account for about 70 % of the industrial CO_2

Abbreviations: CO_2, Carbon dioxide; GHG, Greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; IEA, International Energy Agency; CCS, Carbon capture and storage; CCU, Carbon capture utilization; CCUS, Carbon capture, utilization and storage; CDR, Carbon dioxide removal; MC, Mineral carbonation; SCM, Supplementary cementitious material; SDG, Sustainable Development Goals; CBM, Cement-based materials; OPC, Ordinary Portland Cement.

[*] Corresponding author at: Department of Environment, Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
E-mail address: faradiella@upm.edu.my (F.M. Kusin).

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emissions (IEA, 2021b).

CCUS is becoming a future outlook in technological path of carbon sequestration, a new concept that synergizes CCS (carbon capture and storage) and CCU (carbon capture utilization), to offer more utilization potential of the captured carbon (IEA, 2022; IEA, 2021b; Hills et al., 2020). CCUS specifically makes use of the captured carbon into usable products or materials that permanently store the CO_2, such as in building and construction materials. CCUS via mineral carbonation (MC) has received particular attention in recent decades as a branch of carbon sequestration or carbon dioxide removal (CDR) technology. By means of MC, CO_2 is captured and fixed into stable carbonates to be kept permanently or turned into a usable product for revenue generation (Syed-Hasan et al., 2021). This will prevent the release of CO_2 back into the atmosphere or known as carbon leakage over time. However, the greatest challenges to the adoption of MC are the large amount of costs and energy consumption (Liu et al., 2021).

CCS is an environmentally-sound perspective to permanently store CO_2 in carbonated form. This technology has been applied mainly utilizing alkaline industrial wastes such as cement kiln dust, steel slag, blast furnace slag, construction and demolition waste, and fines from aggregate production (Renforth et al., 2011, 2015). A number of researchers have proposed CCS as the solution for capturing and storing carbon for long term in stable carbonate form by means of MC (Jacobs and Hitch, 2011). This process requires the search for natural (targeted) minerals to enable the carbonation process, whether it takes place in-situ or in a MC plant. While seeking for a targeted mineral can be resource- and energy-intensive, an alternative to this is by making use of recovered minerals in mining waste. By this means, potential minerals that are available can be utilized as agent for CO_2 capture without purposely mining the desired minerals. The key to the success of this approach is the CO_2 reaction with available silicate and/or oxide minerals, and manipulation of the process through accelerated MC (Stopic et al., 2018; Gabrielli et al., 2020; Ruhaimi et al., 2021). Silicate-bearing minerals such as magnesium and calcium silicates have been commonly used, as reactive minerals in transforming CO_2 into stable carbonates. It has been known that despite being regarded as waste material, there is availability of valuable minerals that can act as precursors for the carbonation process. Thus, the current review emphasizes the recovery potential of silicates/oxides in mining waste, coupled with accelerated MC to sequester more CO_2 for long-term carbon capture and storage.

Additionally, CCU has emerged to add value to the end product of carbon capture. CCS and CCU aim at permanently capturing CO_2 to prevent it from re-entering the atmosphere, however, the final storage of the captured CO_2 is different. CCS shifts the captured CO_2 to a permanent storage for long term, while CCU produces useful product such as storing CO_2 in cementitious materials for construction industry, as synthetic fuels or other materials (Huang et al., 2019; Alshalif et al., 2021; Othman et al., 2021; Zhu et al., 2020). MC has been advocated as an ideal CCS and CCU approach where CO_2 is captured as stable carbonate and can be further used in numerous applications for product development (Jacobs and Hitch, 2011; Bobicki et al., 2012). Mining waste is potentially useful for both CCS and CCU but the latter provides opportunity for revenue generation apart from removing CO_2 from the atmosphere. The process of trapping and storing CO_2 will help stabilize concentrations of CO_2 that would otherwise be released into the atmosphere.

On the other hand, CCUS adoption has become the new prospects for the mining sector as this industry produces a significant quantity of waste and GHG emissions annually. This can be seen across the mining value chain from mineral exploration, mining, extraction, processing and mineral distribution. Mining industry is considered carbon-intensive which has contributed to the rising CO_2 level in the atmosphere. Despite being a major global industry, mining-related problems such as extensive CO_2 emissions and waste accumulation prevail (Kusin et al., 2021). Mining industry has yet to align their actions with the United Nation's Sustainable Development Goals (SDG) in achieving the global target of net-zero by 2050. Therefore, mining industry needs to integrate elements of environment, social and economy, and the SDG targets to ensure long-term sustainability (UNDP, 2016). Mining waste utilization for CO_2 sequestration offers long-term sustainability of mineral recovery for environmental benefits (SGD13-Climate Action, SDG12-Responsible Consumption and Production, and SDG7-Affordable and Clean Energy), and its utilization contributes to economic benefits which is in-line with circular economy concept (SDG9-Infrastucture, Innovation and Industrialization, SDG8-Decent Work and Economic Growth). To tackle both issues of CO_2 emissions and waste accumulation, mineral carbonation (MC) can be a choice if operated under feasible circumstances, i.e. with considerations to reduce energy and cost implications (Assima et al., 2012, 2013). Mining residues provide an opportunity for mineral resource recovery and improve economic values for the industry by integrating it with technological advancement.

2. Literature review

2.1. Fundamental mineral carbonation for carbon sequestration

CCS by MC can help decrease CO_2 emission by permanently storing it into solid carbonates (Arce et al., 2017; Jorat et al., 2015a, 2015b, 2017; Li and Hitch, 2017; Manning et al., 2013; Moosdorf et al., 2011; Washbourne et al., 2015). MC or known as weathering is a natural process that removes CO_2 from the air where mineral alkalinity neutralizes the acid (Pan et al., 2012). Carbon sequestration by MC is the process that imitates the natural rock weathering which has played a major role in reducing concentration of CO_2 in the atmosphere (Pan et al., 2012). The MC reaction occurs when potential divalent cations such as magnesium, calcium and iron silicate minerals react with CO_2 to form magnesium, calcium and iron carbonates and silica as shown in the following reaction (Arce et al., 2017; Gras et al., 2017; Vogeli et al., 2011):

$$(\mathrm{Ca/Mg/Fe})\mathrm{SiO_3} + \mathrm{CO_2} \rightarrow (\mathrm{Ca/Mg/Fe})\mathrm{CO_3} + \mathrm{SiO_2} \tag{1}$$

From the reaction, carbonates produced by MC are thermodynamically stable (Gerdemann et al., 2007), where it avoids the CO_2 from being released back into the environment. Examples of stable carbonate minerals are dolomite ($CaMgCO_3$), magnesite ($MgCO_3$), calcite ($CaCO_3$) and siderite ($FeCO_3$) that are produced from the CO_2 fixation (Ibrahim et al., 2019). Note that these are the primary carbonate minerals, i.e. those that are formed through geological processes; however, secondary carbonate minerals are formed after manufacturing (Power et al., 2017).

CO_2 sequestration by MC can be achieved via two pathways i.e., mineral weathering (in-situ, active or passive carbonation) or simulated (accelerated) weathering under controlled environments (ex-situ, direct or indirect carbonation), as shown in Fig. 1. This technology provides a promising choice for long-term CO_2 reduction, as atmospheric CO_2 is converted into carbonate minerals either by in-situ or ex-situ carbonation processes.

Theoretically, in-situ MC includes CO_2 injection from the gas flows into rocks or soils (active) or by means of a natural (passive) CO_2 sequestration in the vicinity of the mine site, with the purpose of permanently storing the captured CO_2 (Wilson et al., 2009; Assima et al., 2013; Harrison et al., 2013; Manning et al., 2013; Jorat et al., 2018). During in-situ MC, CO_2 will directly react with the host rock (preferably basalt and ultramafic rocks) that are rich in divalent cations (Ca, Mg, Fe) and low in silica. Ultramafic rocks are typically considered to be one the most promising rocks for CO_2 sequestration due to the high content of Mg-bearing silicate minerals (Declercq et al., 2023; Paulo et al., 2023). It is important to choose the host rock to inject CO_2 such as those that can easily dissolve the cations and have sufficient pore density and permeability for long-term CO_2 storage. A study found the potential for passive CO_2 sequestration through weathering of kimberlite mine tailings which can be beneficial to offset almost 100 % of the mine's CO_2 equivalent

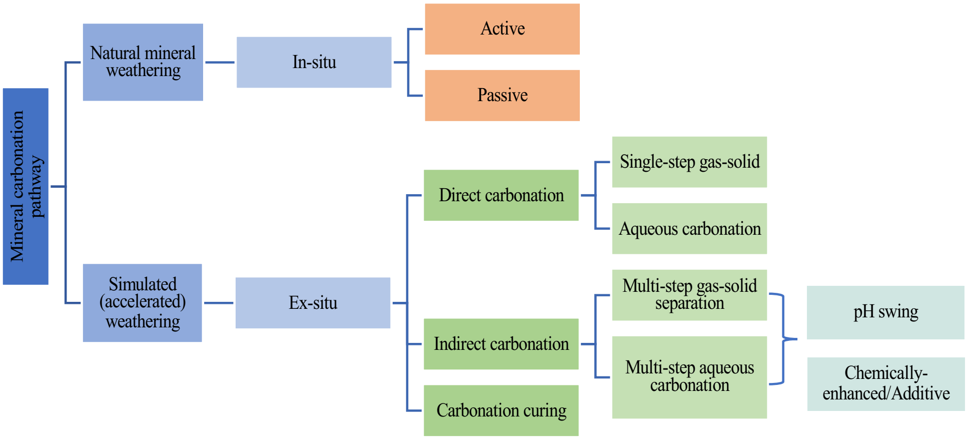

Fig. 1. Mineral carbonation pathway showing two major paths by means of natural mineral weathering and simulated (accelerated) weathering. Accelerated mineral carbonation can be achieved via direct or indirect carbonation and carbonation curing methods.

emissions (Mervine et al., 2018). However, among the challenges of in-situ MC is due to leakage problems when CO_2 is stored underground, which requires continuous monitoring of storage sites. Another study has explored the potential of CO_2 mineralization of ultramafic mine tailings by means of an in-situ, direct MC, suggesting long-term feasibility of the method, but also suggested that reaction can be enhanced under accelerated condition (Power et al., 2020). Hamilton et al. (2020) found that acid-leaching treatment might be useful to accelerate CO_2 sequestration of ultramafic mine tailings in a passive MC. The more recent study has developed a framework for mineral carbonation potential (MCP) calculation for estimation of CO_2 capacity in mining operations based on oxide minerals availability (Jacobs et al., 2023). Note that however, in-situ carbonation under the ambient atmosphere of a mining site is still a challenge due to the slow process kinetics and other on-site uncertainties (Bullock et al., 2021). Carbonation efficiency of in-situ passive carbonation of mine waste has yet to be determined and compared with those of ex-situ processes. Although passive carbonation is less complicated than other MC methods, the CO_2 uptake ability of alkaline wastes for in-situ passive carbonation is limited due to numerous factors, e.g. slower silicate mineral dissolution kinetics, limited CO_2 entry into alkaline wastes, and passivation of reactive surfaces (Khudhur et al., 2022). Nevertheless, in-situ MC has advantages over the ex-situ process in terms of the cost elimination for transporting the waste material and the natural process requires no additives or solvent to accelerate carbonation reaction.

Whereas, ex-situ MC takes place outside or nearby the mine site, which consumes silicate-containing minerals as the sequestering agent for permanent storage or production of new materials. The ex-situ MC is the method that mimics natural weathering in sequestering CO_2 through manipulation of several factors. This requires incorporation of parameters to facilitate the process such as particle size, temperature, pH, CO_2 partial pressure, experiment time, and the presence of catalyst and water (Sanna et al., 2014; Yuen et al., 2016). Compared with in-situ process, the ex-situ carbonation offers more benefits as the process can be manipulated to enhance sequestration capacity while producing usable or revenue-generating products (Bodénan et al., 2014).

Direct carbonation has two process routes namely gas phase and aqueous phase. Although direct gas-solid carbonation is a much simpler process compared to direct aqueous carbonation, the reaction rate is too slow and is not recommended for a big-scaled project. Researchers have used direct aqueous MC to evaluate the effectiveness of materials for CO_2 sequestration and discover variety conversion efficiencies under different experimental conditions (e.g. Azdarpour et al., 2014; Yan et al., 2015). For instance, minerals such as wollastonite, red gypsum and olivine (calcium- and magnesium-bearing minerals) have been used under varying conditions (adjustments of reaction temperature, pressure, particle size, solid-liquid ratio, reaction time). Typically, a high carbonation efficiency is associated with the increase in temperature and pressure, and decrease of particle size during the conversion process. Variation of process efficiency and carbonate purity at higher temperatures has been seen in some studies (e.g. Azdarpour et al., 2014, 2018; Rahmani, 2020).

Indirect carbonation includes multi-step carbonation processes which are extraction and precipitation that occur separately to improve process efficiency (Chang et al., 2012; Han et al., 2015). This process allows the dissolution (leaching) and carbonation (carbonate precipitation) to be controlled separately (Jacobs, 2014; Li and Hitch, 2015). The advantage of controlling both processes separately is that the unwanted oxides other than magnesium, calcium or iron oxide can be removed to avoid interfering with the overall process, which can improve the carbonation efficiency. Leaching or mineral extraction enables better dissolution of essential minerals (i.e. Ca, Mg and Fe) to be optimally present and available in solution to undergo carbonation. Additives and solvents (i.e. acids, bases and ammonium salts) are used to facilitate cations leaching from respective minerals and reacted with CO_2 resulting in carbonate precipitation (Bobicki et al., 2015; Ukwattage et al., 2015). Enhancement in carbonate precipitation can be made through a pH-swing method that combines the use of reagents to optimize the carbonation process (Sipilä et al., 2008; Reynes et al., 2021). Adoption of mild conditions or low-reaction conditions have been the focus of the more recent studies to address the issues of cost and energy consumption (Kemache et al., 2017; Yadav and Mehra, 2017; Coppola et al., 2022). Evolutionary MC process is further discussed in Section 4.2, which has identified a new trend in MC applications which emphasizes the utilization and product quality of the captured carbon. For instance, 3-step carbonation processes, i.e. leaching-carbonation-carbonate regeneration (calcination) have been introduced to optimize carbonate conversion and produce high-purity carbonates (Mendoza et al., 2019a; Woodall et al., 2021; Rahmani, 2020; Reynes et al., 2021; Ho et al., 2022).

2.2. Potential divalent cations for carbonation reaction

In the context of CCS, carbonate is considered a reservoir or sink for carbon storage because it is highly available in geological sites, in the form of primary or secondary carbonate minerals. Primary carbonate minerals occur as a result of geological processes, while secondary mineral carbonates occur after manufacturing (Power et al., 2013). Through MC, secondary minerals are formed as a result of the mineralization of primary minerals that release ions, e.g. H^+, Mg^{2+} and Ca^{2+}, then interact with CO_2 to form stable carbonates (Lechat et al., 2016; Power et al., 2013).

Divalent cations are in some circumstances hard to obtain and require silicate minerals as major sources of MC. The availability of primary and secondary minerals containing potential divalent cations act as precursors for MC. It has been learned that mining waste is composed of; (i) alkaline metal-bearing silicate minerals (ii) silicate residue rock and (iii) hydroxide minerals, rich in magnesium and calcium to enable carbonation reactions (Power et al., 2013). The abundance of Mg and Ca silicates as well as their insoluble nature makes it favourable for MC (Bobicki et al., 2012; Ibrahim et al., 2019; Vogeli et al., 2011). The reaction of Mg and Ca oxides with CO_2 produce is considered ideal for MC as shown in reactions (2) and (3):

$$MgO + CO_2 \rightarrow MgCO_3 \tag{2}$$

$$CaO + CO_2 \rightarrow CaCO_3 \tag{3}$$

Therefore, availability of Mg and Ca in natural minerals of rocks and industrial waste can be useful to mimic MC (Ibrahim et al., 2019). For example, olivine (reaction 4), serpentine (reaction 5) and wollastonite (reaction 6) are the natural silicate minerals commonly used for MC (Bobicki et al., 2012).

$$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2 \tag{4}$$

$$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O \tag{5}$$

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2 \tag{6}$$

Metamorphic rocks and basic rocks may contain potentially reactive Ca and Mg cations for carbonation reaction such as wollastonite, laumontite, tremolite, olivine, diopside and anorthite. Industrial waste such as cement clinker contains Ca-rich minerals, e.g. portlandite, larnite and rankinite, while red mud contains Ca- and Mg-rich minerals like gypsum, chlorite, brucite and chantalite, which can form Ca and Mg carbonates by reacting with CO_2. The carbon sequestration capacity of these minerals varies depending on the Mg/Ca/Fe content. Most of the reactions are governed by the available silicate-bearing minerals, i.e. Mg- and Ca-silicates, whereas carbonation of Fe-based minerals are associated with the availability of Fe oxide minerals, such as hematite and magnetite. The synthesis of siderite will produce bicarbonate ion, while the reactions between hematite (reaction 7) and magnetite (reaction 8) with CO_2 will produce iron carbonate, as given below (Mendoza et al., 2019a):

$$Fe_2O_3(s) + Fe(s) + 3CO_2(g) \rightarrow 3FeCO_3(s) \tag{7}$$

$$Fe_3O_4(s) + Fe(s) + 4CO_2(g) \rightarrow 4FeCO_3(s) \tag{8}$$

Moreover, siderite calcination will yield magnetite, carbon and iron, which can reversely reabsorb CO_2 in multiple carbonation-calcination cycles (Mendoza et al., 2019a). This is shown as in the following reactions:

$$6FeCO_3(s) \rightarrow Fe_2O_3(s) + C(s) + 5CO_2(g) \tag{9}$$

$$4FeCO_3(s) \rightarrow Fe_3O_4(s) + Fe(s) + 4CO_2(g) \tag{10}$$

$$2\ Fe_3O_4\ (s) + C(s) + 5\ CO_2\ (g) \rightarrow 6\ FeCO_3(s) \tag{11}$$

The utilization of alkaline earth minerals, especially iron oxides, may be a viable option for long-term CO_2 sequestration. Carbonation processes are exothermic, whereas decomposition processes of carbonate are endothermic which enables the development of a cyclic process (Mendoza et al., 2019b). Therefore, utilization of Fe oxides which are abundant from industrial waste can be relevant and provides a new perspective as sorbent for CO_2 capture.

Furthermore, utilization of industrial waste has more benefits because they are cheaper, plentiful, require less pre-treatment and are more reactive than natural minerals (Bobicki et al., 2012; Ibrahim et al., 2019). By using waste materials, the needs for raw minerals can be reduced and the impact on the environment can be minimized. Despite this, both natural minerals and industrial waste can be useful to facilitate mineral carbonation.

2.3. *Carbon sequestration via carbonation curing*

Another pathway of CCUS for industrial waste is through the carbonation curing process. Theoretically, carbonation curing has two important roles; i) to enhance the strength and durability of cement matrix, thus making it usable as a green construction material and ii) a method that mimics MC to accelerate carbonation reaction of cement-based materials (CBM) to capture more CO_2 for long-term storage. With carbonation curing, the carbonation rate can be accelerated by 400 to 1600 times compared to the passive carbonation rate (Power et al., 2017). In carbonation curing, the process of carbonation starts at an early stage of cementitious material and will produce calcium carbonate and calcium-silicate-hydrate, C-S-H (main product of cement hydration), which can compensate the lower strength caused by the use of mineral admixtures (Qin et al., 2019). Carbonation curing is also regarded as a new way of producing high-strength cement binder with integration of waste recycling and CO_2 sequestration (Mo et al., 2017). The method has been known to be beneficial in replacing moist and steam curing, i.e. reduction of water consumed by 91 and 97 %, respectively (El-Hassan, 2020). Replacing steam curing with carbonation curing in concrete blocks fabrication can reduce up to 30 % CO_2 emission (Huang et al., 2019). To date, various applications in CBM have been applied as a means for material quality improvement, but the capacity of CO_2 capture in these CBMs for CCUS application has not been widely studied. This is particularly important for estimation of long-term CO_2 capture and in response to global estimates of CO_2 reduction from the construction industry.

From another point of view, CO_2 capture by means of carbonation curing has been explored in the more recent years. As cement and other construction materials produce high CO_2 into the atmosphere, approximately 7 % of global energy-related CO_2 emissions come from the production of cement (IEA, 2022). Nevertheless, recovered CO_2 can be utilized as a curing agent in the production of carbonated concrete products for long term CO_2 capture (El-Hassan and Shao, 2014). The concept of carbonation curing is almost similar to the MC process, where CO_2 is stored in concrete as thermodynamically stable $CaCO_3$ or in other CBMs. The capacity of CO_2 storage in CBMs have been discovered for calcium carbonate binders (Mo et al., 2019), cement mortar (Qin et al., 2019; Alimi et al., 2022), magnesium oxychloride cement boards (Power et al., 2017), cement-bonded cellulose fiberboards (He et al., 2019), concrete masonry block (El-Hassan and Shao, 2014; Ghouleh et al., 2017) and mortar mixes (Sharma and Goyal, 2018), among others. However, not all of these were using waste materials as the sequestering agent. On the other hand, the use of mining waste is similarly important as additional binder in CBM such as concrete, brick and blocks that will enhance the material strength and increase CO_2 storage of the carbonated product.

3. Methods

3.1. *Research gaps and objectives*

This review delves into the opportunity of CCUS with integration of mining waste as feedstock for carbon sequestration, and utilization of the captured carbon into revenue-generating products. Specifically, this review highlights dual opportunities of mining waste utilization in CCUS by means of accelerated MC and carbonation curing. While it is known that MC can be achieved by means of direct and indirect carbonation, the efficiencies of these sequestration routes are still limitedly studied. This is particularly important for current adoption of the technology and for future projection of their potential sequestration capacity in meeting the global net-zero target. Mining waste has been widely utilized as supplementary cementitious material in concrete products, however, its utilization for permanent CO_2 storage, which is a new perspective in CCUS application, is not widely investigated. Therefore, this review aims to i) identify potential sequestration capacity of mining and other industrial waste ii) determine carbonation efficiency and CO_2 capture capacity of MC and carbonation curing routes iii) evaluate the cost and environmental challenges of MC and carbonation curing iv) assess the opportunity for mining waste utilization via CCUS.

Thus, this review is emphasized on new insights and opportunities for mining waste utilization via CCUS, to sequester more CO_2 and in meeting the global CO_2 reduction targets. Consequently, this will provide a sustainable option for CO_2 and waste reduction as well as to counterbalance the energy-cost implications through the production of new material or revenue-generating products. The overall review concept and scope of review is illustrated in Fig. 2.

3.2. Review strategy

This review adopted a systematic literature review following a review methodology as shown in Fig. 3. Article search was performed using the “advanced document search” in the Scopus database. The Scopus database was used for the literature search as this is a well-established, multidisciplinary database that is widely applied in bibliometric analysis. The article search covers the publications between the timespan of 2010 to 2023, where the trend of the topics searched shows an increasing interest by the global researchers. The document types in the literature search included peer-reviewed articles and journals written in English covering the subject areas of engineering, environmental science, chemical engineering, energy, chemistry and materials science.

Initial screening of the articles was done based on the title, keywords and abstract. The keywords used for searching the relevant literature were “industrial waste” AND “carbon capture and storage” OR “carbon sequestration” resulted in >2000 related articles. The search strings were then refined to screen the articles based on the critical targets such as “mineral carbonation”, “industrial waste”, “mining waste”, “accelerated carbonation”, carbonation curing”, “carbon capture and utilization” and “CCUS” to exclude non-relevant articles. Manual content analysis was undertaken to select articles most relevant to research focus including carbon sequestration by mineral carbonation, adoption of accelerated mineral carbonation for carbon capture, adoption of carbonation curing for carbon utilization, carbonation efficiency and CO_2 capture capacity. Remaining articles (106) were then selected for a detailed review to restructure the review systematically into categories of topics. The publications search resulted in the following categories of topics that will assist in the formulation of a framework for mining waste utilization via CCUS technology to meet the global CO_2 reduction target:

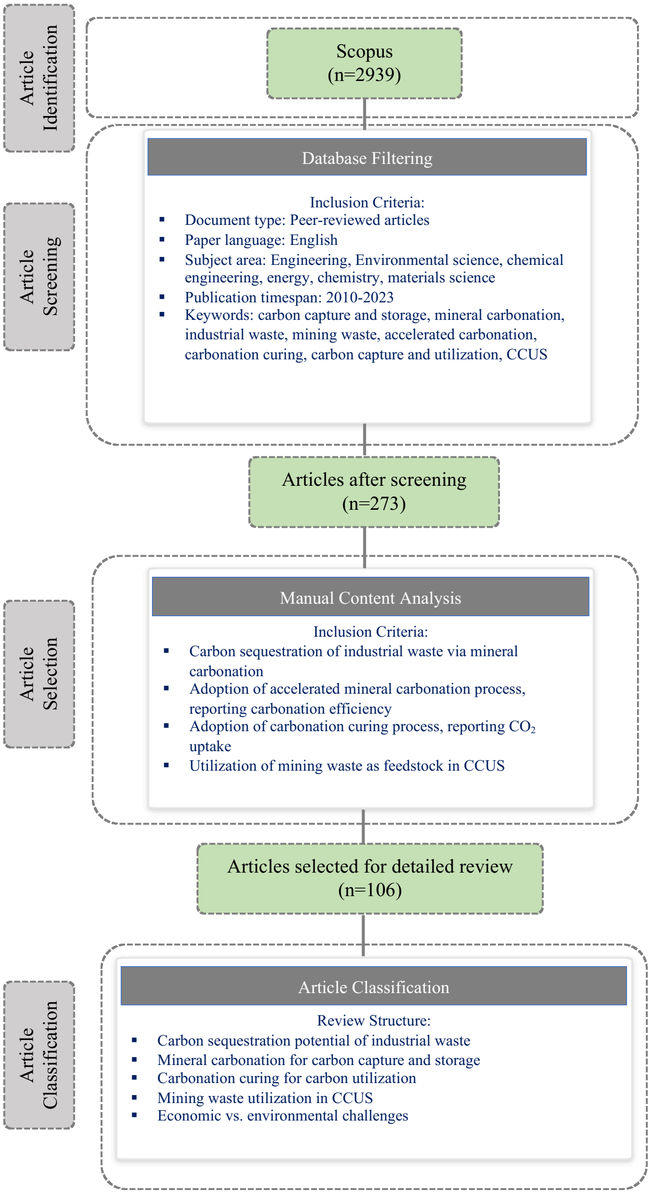

Fig. 3. Flow chart of a systematic review methodology.

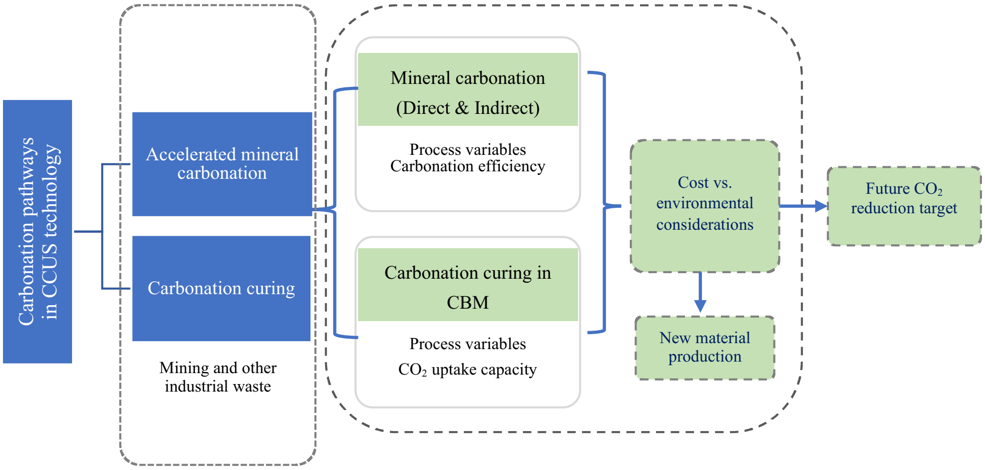

Fig. 2. Overall review concept and scope of the review.

- Carbon sequestration potential of mining and other industrial waste
- Mineral carbonation efficiency for carbon capture and storage
- Carbonation curing capture capacity for carbon utilization
- Mining waste utilization in CCUS
- Economic versus environmental challenges

3.3. *Data analysis*

Further synthesis of data was undertaken using statistical correlations to strengthen the findings by identifying the relationship between the factors influencing MC. This includes the relationships between MC carbonation efficiency and oxide minerals availability, CO_2 uptake of CBM and carbonation time, and compressive strength of CBM as influenced by carbonation curing. Evaluation system for the estimation of future target of CO_2 reduction by means of CCUS was established based on two scenarios, i.e. analysis of current rate of direct and indirect MC, and integration with carbonation curing. Current rate of MC efficiency and carbonation curing CO_2 capture capacity were analyzed and integrated with the global estimates for CCS and CCU applications. The final output from the review synthesis is presented as a framework for mining waste utilization and considerations through an integrated CCUS with long-term prospects of CO_2 reduction and new material production.

4. Results and discussion

4.1. *Carbon sequestration potential of industrial waste via mineral carbonation*

Industrial wastes such as mining waste, cement kiln dust, construction and demolition waste, iron slag, steel-making slag, fly ash and red mud are potential silicate mineral sources for MC as they contain significant amount of carbonate-forming MgO, CaO, and FeO compounds (Table 1). Thus, the total mean global production of these wastes is estimated to be around 18,273 Mt./y with a total carbonation potential of 5189 MtC/y (~28.4 %). The potential carbon sequestration from mineral recovery was calculated as the maximum capacity with the assumption that all available calcium, magnesium and iron oxides are converted into carbonate, i.e. one mol of cation captures one mol of carbon, however this is not often the case in real practice (Renforth et al., 2011). The estimation here is also based on the assumption of 100 % mobilization of fluid soluble cation from the waste material in the alkalinity generation during the carbonation reaction (Bullock et al., 2021). Mine waste contributes to about 62.94 % of the total global production of industrially-derived silicate minerals, potentially useful for carbonation (Fig. 4). The resultant carbon sequestration potential is estimated to be 53.96 % which is derived on the basis of available silicates containing CaO, MgO and FeO. The cement kiln dust and construction and demolition waste contribute to 19.85 % and 10.65 % of the waste-silicate production, respectively, corresponding to 24.09 % and 15.42 % of carbon sequestration potential. Additionally, it has been estimated that about 7–17 Gt/y of alkaline wastes are produced globally, and by 2100, around 2.9–8.5 Gt/y CO_2 can be captured annually (Renforth, 2019).

It can be seen that mine waste has the highest sequestration capacity of all other waste types, potentially sequestering 2800 MtC/y from its total production of 13,000 Mt./y (Fig. 5 and Table 1). This is amounted to 80 % of the total CO_2 emissions from mining industry, i.e. 3.5 Gt/y. This is followed by cement kiln dust and construction and demolition waste, with 1250 MtC/y and 800 MtC/y, respectively, which are notably reflected by the high amount of CaO, i.e. 56.5–63.5 wt%. This can offset about 80.6 % of the CO_2 emissions from cement industry (2580 Mt./y). Whereas, FeO seems to be similarly important as CaO for carbonization of steel slag, iron slag and red mud, potentially sequestering 31–125 MtC/yr. The greatly high mine waste production makes it potential as a CO_2 sequestering agent in long-term CCUS ventures. This is because the reactive minerals such as CaO (28.3 wt%), MgO (2.9 wt%) and FeO (28.4 wt%) are abundantly available from various abandoned and active mine sites globally, which can act as precursor for MC. The variation of these compounds in mine waste is because of the nature of waste, i.e. metallic or non-metallic minerals. Their readily fine fraction is also useful to increase the rate of carbonation reactions (Sipilä et al., 2008; Pan et al., 2012). As noted, the contribution of FeO is essentially as important as CaO and MgO in the carbonation of mine waste, suggesting that variety reactive minerals offers more potential for carbonation to take place.

Table 1
Carbon sequestration potential from different silicate mineral sources of industrial waste.

Waste material	Divalent cation content (wt %)[a]	Global production amount (Mt/y)[a]	Carbon sequestration (MtC/y)[b]	Reference
Cement kiln dust	56.5 % CaO 1.6 % MgO 2.0 % FeO	4100	1250	Al-Bakri et al., 2022
Construction and demolition waste	63.5 % CaO 1.2 % MgO 3.5 % FeO	2200	800	Akhtar and Sarmah, 2018
Ground granulated blast furnace slag	38.5 % CaO 7.0 % MgO 1.5 % FeO	280	66	CW Group, 2021
Steel slag	46 % CaO 7.5 % MgO 25 % FeO	225	92	USGS 2021
Iron slag	47.5 % CaO 8.0 % MgO 20.5 % FeO	345	125	USGS 2021
Red mud	12.7 % CaO 0.25 % MgO 35.5 % FeO	120	31	Silveira et al., 2021
Fly ash	2.75 % CaO 1.1 % MgO 7.2 % FeO	367	20	Dwivedi and Jain, 2014; Jin et al., 2021
Stainless steel slag	50 % CaO 8.5 % MgO 3.5 % FeO	16	5	Holappa et al., 2021
Mine waste	28.3 % CaO 2.9 % MgO 28.4 % FeO	13,000	2800	Bullock et al., 2021
	Total	**18,273**	**5189**	

[a] Values reported are mean data from available references.
[b] Calculated based the available cation content; 1 mol of cation that can capture 1 mol of carbon.

4.2. *Mineral carbonation for carbon capture and storage*

4.2.1. *Carbonation efficiency of direct versus indirect mineral carbonation*

Performance comparison between direct and indirect MC in terms of the carbonation efficiency and their operating conditions from the literature is presented here (Tables 2 and 3). For both approaches, comparison between natural minerals and industrial waste as feedstock materials can be seen (Fig. 6).

By direct carbonation, the carbonation efficiency of the waste materials (including mine waste, steel slag, waste lime, waste concrete, carbide slag, red mud and coal fly ash) is in the range of 8.5–72.0 % (Li and Hitch, 2015; Kemache et al., 2017; Bobicki et al., 2015; Yadav et al., 2010; Ukwattage et al., 2015; Ghacham et al., 2016; Revathy et al., 2016; Woodall et al., 2021; Coppola et al., 2022). Carbonation efficiency can achieve between 12.5 and 83.5 % if using natural minerals such as

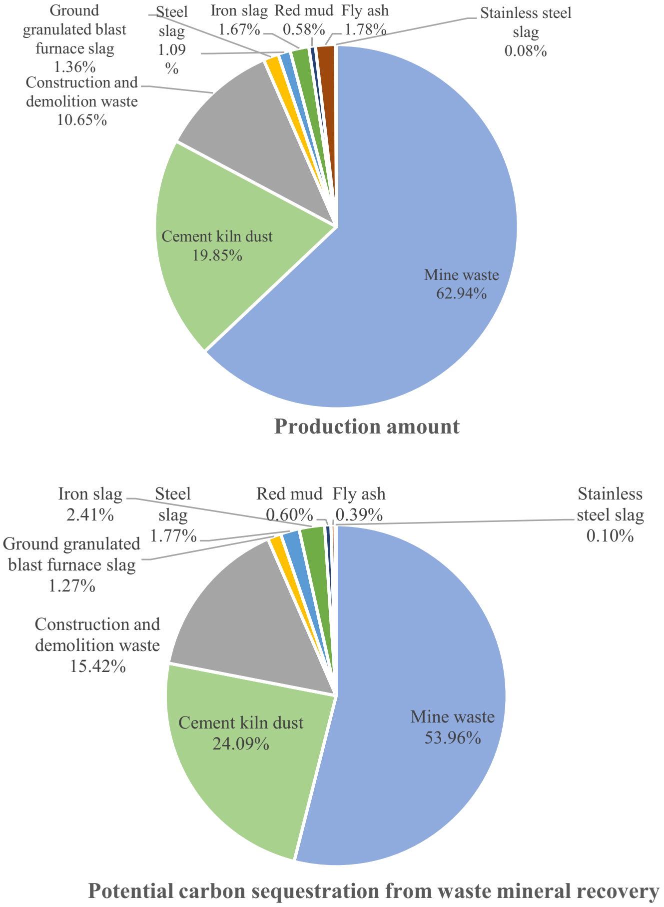

Fig. 4. Global production amount of industrial waste versus estimated carbon sequestration potential derived from beneficial silicate mineral recovery. The large proportion of mine waste suggests its great potential as a sequestration agent for long-term carbonization through accelerated MC.

wollastonite, olivine, serpentine, limestone, lizardite, red gypsum, hematite and magnetite (Han et al., 2015; Yan et al., 2015; Azdarpour et al., 2018; Benhelal et al., 2018; Mendoza et al., 2019a). The lower carbonation efficiency of waste materials compared to natural minerals has been anticipated because of the slow mineral dissolution rate and weathering of the silicate-hosting minerals of most waste materials (Bullock et al., 2021). Thus, an accelerated MC is highly recommended to improve the process efficacy. Minerals such as CaO, MgO and Fe_2O_3 play important roles in MC. Regardless of the types of waste materials, it was found that there is a strong correlation between carbonation efficiency and CaO availability from the data ($r = 0.72$; $p < 0.01$), suggesting that this oxide mineral is essential to facilitate MC.

Clearly, the indirect MC resulted in comparatively high carbonation efficiency as opposed to the direct MC regardless of the types of feedstock materials (Fig. 6). Using natural minerals, a higher carbonation efficiency was found, i.e. between 68.3 and 91.1 %, compared to 10–92.6 % for waste materials. As anticipated, use of natural minerals as feedstock would provide a higher carbonation rate due to essential minerals availability, and hence a higher carbonation efficiency, i.e. around 1.5–9.8 % higher than waste materials. Overall, the average carbonation efficiency for indirect carbonation is 81.2 % compared to 45.1 % for direct carbonation.

Given the limited data on carbonation efficiency with mine waste, more research is required to obtain a better understanding of the underlying mechanisms of direct MC for mine waste. Manipulation of process variables can be useful in order to enhance MC efficiency for mine waste. Understanding the carbonation efficiency is deemed important for current and future adoption of MC technology, and how this is reflected by the operating conditions of the processes.

4.2.2. *Important considerations for mineral carbonation application*

The major challenge in MC adoption is to optimize the carbonation reaction to sequester more CO_2. Evolutionary MC has seen increasing studies about process variables and optimization of operating conditions in the earlier research (Chang et al., 2012; Han et al., 2015; Li and Hitch, 2015; Bobicki et al., 2015; Ukwattage et al., 2015). Attempts to adopt mild conditions or low-reaction conditions (e.g. ambient pressure and temperature) have been the focus of the more recent researches (Yan et al., 2015; Kemache et al., 2017; Yadav and Mehra, 2017; Ghacham et al., 2016; Revathy et al., 2016; Coppola et al., 2022). This is to complement the need for a more efficient MC to counterbalance the cost implication associated with high energy consumption. Recent researches on MC have been advancing to the application of multi-stage carbonation to improve process efficiency (e.g. higher carbonation efficiency and CO_2 capture capacity) while emphasizing on the utilization of the captured CO_2 (Mendoza et al., 2019a; Woodall et al., 2021; Rahmani, 2020; Reynes et al., 2021; Ho et al., 2022). Most of these studies adopted multi-step carbonation processes (e.g. leaching, carbonate precipitation (carbonation) and solution regeneration or calcination). This will be in line with the circularity concept to maximize CO_2 conversion and to enhance minerals utilization.

Notwithstanding this, optimizing operational conditions of MC processes is the key to efficient CO_2 conversion. The process can be facilitated by controlling operating temperature, CO_2 pressure, pH, particle size, solid-liquid ratio, reaction time and use of additives or acids/bases to be at optimum conditions (Ibrahim et al., 2019; Olajire, 2013; Woodall et al., 2019). Although carbonation efficiency of direct MC is lower, the method may be more favourable than indirect MC because of its simple and easy operation. However, additional research on the increased carbonation technique and kinetics are required to improve the fundamental knowledge of direct carbonation (Wang et al., 2021). Recent studies have shown that direct carbonation with manipulation of the controlling variables, e.g. temperature, CO_2 pressure, particle size fraction and pH can achieve comparable performance as those of the indirect process (Stubbs et al., 2022; Coppola et al., 2022; Kusin et al., 2023).

By means of direct MC, reaction temperature between 90 and 160 °C can be favourable to reach carbonation efficiency of between 65 and 72 %, with CO_2 pressure < 10 bar and particle size <65 μm. Through indirect MC, alongside this combination of carbonation conditions, the more crucial process variables are the type of extractants or additives used or other activation methods during leaching and pre-carbonation step. This is important to enhance cation dissolution prior to carbonation and to fasten the reaction kinetics.

For instance, ammonium acetate and ammonium nitrate are effective solvents that can be used under ambient pressure and temperature (Jo et al., 2014). Similarly important is pH adjustment to enable maximum 100 % CO_2 conversion efficiency even under low-reaction conditions (e.g. ambient temperature, 8 bar) (Azdarpour et al., 2015; Reynes et al., 2021). Use of catalysts such as mono-ethanolamine (MEA), 2,2′-bipyridine [Fe (bipy)3]$^{2+}$ and bipolar membrane electrodialysis (BPED) to complement the leaching step can be useful to enhance reaction kinetics thus resulting in high carbonation efficiency of >90 % (Rahmani, 2020; Ho et al., 2022). Detailed information on process variables and their carbonation efficiency are summarized in Tables 2 and 3 for direct and indirect MC, respectively.

4.3. *Carbonation curing for carbon utilization*

4.3.1. *Carbon dioxide capture capacity from carbonation curing*

Another opportunity for mining and industrial waste utilization in CCUS is through carbonation curing in CBM. In the context of CCUS, the high CaO content in waste materials (Fig. 4), indicates the existence of a

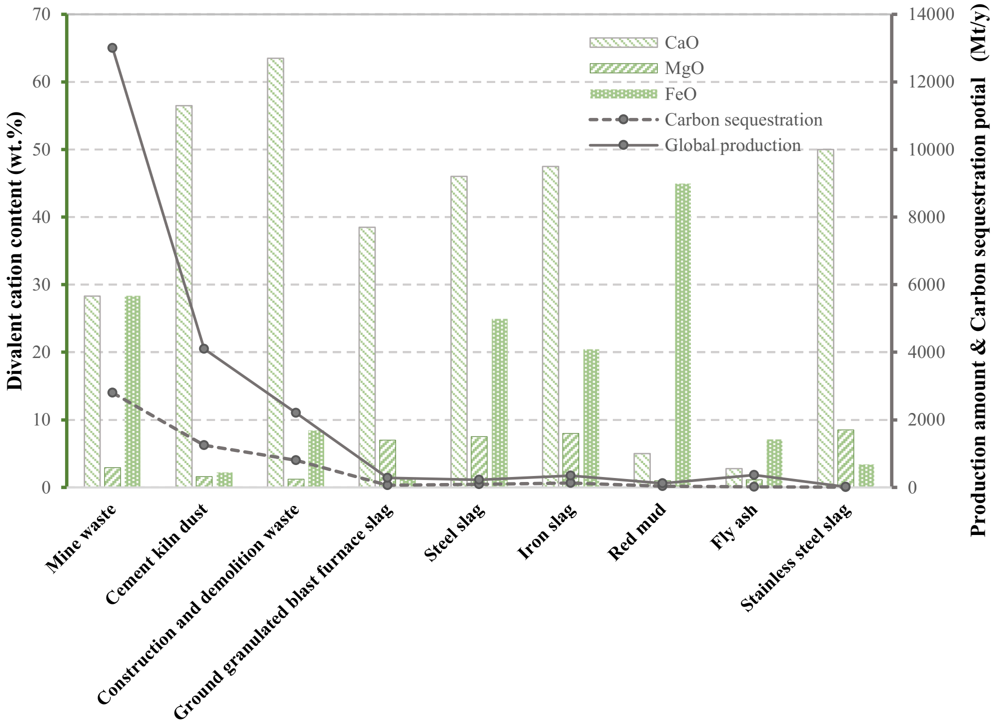

Fig. 5. Carbon sequestration potential as a function of divalent cation content in different types of silicate mineral sources. Alongside CaO and MgO, FeO is similarly important for mineral carbonation with mine waste.

considerable amount of divalent cations for MC with carbonation curing in the production of carbonated or hydrated cement products (Gras et al., 2017). Clearly, the advantages of this innovation with mining and industrial waste utilization in CBM is two-fold; i) waste material as supplementary cementitious material (SCM) for material quality improvement and ii) as agent for CO_2 sequestration to capture more CO_2, which is in line with the concept of circular economy.

On a broader context, industrial waste materials have been widely used for CBM because they are relatively inexpensive and available in large quantities (Ali et al., 2017; Önel et al., 2017). Waste materials are commonly used either as partial cement, sand or aggregate replacement to improve physico-mechanical properties of the cementitious products (Ayaz-Khan et al., 2018; Basit et al., 2018). For instance, waste materials such as fly ash (Önel et al., 2017; Rahman et al., 2018; Shakir et al., 2013), powdered lime (Basit et al., 2018), brick kiln dust (Ayaz-Khan et al., 2018; Riaz et al., 2019), palm oil fuel ash (Mat-Aris et al., 2018; Rahman et al., 2018) and recycled concrete aggregate (Azmi et al., 2017) have been used as SCM. These materials are mostly pozzolanic (Fe_2O_3, SiO_2 and Al_2O_3 $>$ 70 %), and can create more C-S-H bound which increases the CBM compressive strength (Ahmed et al., 2018; Ayaz-Khan et al., 2018).

The adoption of carbonation curing in the production of CBM and corresponding CO_2 capture capacity are as tabulated in Table 4. The types of waste or admixture (materials other than cement, sand and aggregates) used include steel slag, magnesium slag, fly ash, limestone powder, ground granulated blast-furnace slag and brick kiln dust (Mo et al., 2017, 2019; Qin et al., 2019; Alimi et al., 2022; Ghouleh et al., 2017; Wang et al., 2019). It can be seen that the CO_2 capture capacity is between 8 and 46 %. However, little is still known about capacity of CO_2 capture from utilization of mining waste in CBM, suggesting the need for more research in this regard to promote CCUS adoption in the mining industry.

Despite this, the composition of mining waste such as oxides of aluminium, magnesium, calcium, iron and silica are the basic composition for building materials (Wong et al., 2018; Kusin et al., 2020). Therefore, utilization of mining and other industrial waste as supplementary cementitious material in the making of CBMs such as bricks, concrete, and blocks, and others will minimize the environmental impacts often associated with waste accumulation and also help sequester CO_2 permanently. As cement, sand and aggregates are the main composition in CBM, mining waste can be considered an alternative or partial substitute for these compounds and to reduce the demand for natural resources (Azmi et al., 2017; Shakir et al., 2013). Among them, cement is a crucial raw material for the manufacture of CBM, but excessive use of it results in negative impact on the environment, e.g. emissions of CO_2 during cement production and processing (Rahman et al., 2018). Cement replacement with limestone waste for instance, reduces the carbon footprint linked with production of cement by 20 % (El-Hassan and Shao, 2015). Thus, mining waste can be used as partial replacement in CBM to enhance its mechanical and physical characteristics and to counterbalance the impact of CO_2 emissions through carbon sequestration.

4.3.2. *Important considerations in carbonation curing*

Many types of waste or admixtures have been used as SCM and additional binder in accelerating MC in CBM. Among the admixture categories used in CBM include waste-derived binders, calcium-silicate-based cements with little to no hydraulic capacity, MgO cement and non-cementing fillers and artificial aggregates (Zhang et al., 2017). In the adoption of carbonation curing, the emphasis is on the effect of reaction processes on material performance. More specifically, among the admixtures that have been integrated into CBM for estimation of CO_2 capture include magnesium slag, limestone powder, ground granulated blast-furnace slag, fly ash, steel slag and brick kiln dust (Table 3). Except for the in-situ backfilling method of coal mining, other applications using mining waste for CO_2 storage in CBM such as in concrete, mortar or bricks and blocks are still limited. Despite this, mining waste has been reported as a useful SCM to improve material performance and capable of sequestering carbon.

A range of CBMs have been studied as possible sinks for carbon in relation to CCUS applications (Table 3). In view of potential admixtures, it is the mineralogical composition that determines mineral availability

Table 2
Influencing factors for direct mineral carbonation utilizing natural minerals and industrial waste.

Feedstock material	Metal oxide (%)	Solution	Operating conditions	E_{CO2}	CO_2 capture	Reference	Remarks
Limestone	CaO = 98.52	Distilled water	$P_{CO2} = 10$ bar, $T = 150$ °C, p. size <500 μm stirring speed = 600 rpm	65 %	–	Han et al., 2015	Carbonation conversion was enhanced by increasing temperature into the range in which H_2O exists.
Wollastonite Serpentine Olivine	W: CaO = 42.05 MgO = 1.21 S: CaO = 0.04 MgO = 40.59 O: CaO = 5.9 MgO = 32.27	0.6 M $NaHCO_3$	$P_{CO2} = 40$ bar, $T = 150$ °C, p. size<30 μm stirring speed = 600 rpm	W = 83.5 % S = 47.7 % O = 16.9 %	–	Yan et al., 2015	MC under low-medium pressure conditions; wollastonite was the most reactive mineral abut olivine was not suitable for direct aqueous MC.
Red Gypsum	CaO = 32.20 Fe_2O_3 = 28.99	Nanopure-demineralized water	$P_{CO2} = 20$ bar, $T = 200$ °C, time = 1 h p. size <45 μm stirring speed = 1000 rpm	Ca = 12.5 % Fe = 5.7 %	–	Azdarpour et al., 2018	Red gypsum is a very potential feedstock for MC however direct aqueous carbonation resulted in low carbonates purity and carbonation efficiency.
Magnetite hematite	–	Distilled water	$P_{CO2} = 30$ bar, $T = 30$ °C, time = 36 h, stirring speed = 400 rpm	–	610 g CO_2/kg	Mendoza et al., 2019a	Carbonation-calcination process; complete carbonation of iron oxides can be accomplished at room temperature and elevated CO2 pressure.
Lizardite	MgO = 39.9	0.64 M $NaHCO_3$	$P_{CO2} = 150$ bar, T = 150 °C, time = 5 h, solid/liquid ratio = 15 %	33 %	–	Benhelal et al., 2018	Aqueous carbonation under heat activation; higher yield was due to mixing and heat-activated particles.
Mine waste rock, Olivine	MW: MgO = 45.5 Fe_2O_3 = 10.4 O: MgO = 50.9 Fe_2O_3 = 8.4	1 M NaCl or 0.64 M $NaHCO_3$	$P_{CO2} = 60$ bar, $T = 185$ °C, time = 1 h, p. size<106 μm, stirring speed = 1500 rpm liquid/solid ratio = 1	MW = 8.7 % O = 5.2 %	–	Li and Hitch, 2015	Mechanical activation as a pre-treatment method; mechanically activated mine waste exhibits a higher carbonation conversion.
Serpentinite-based tailings	T1: MgO = 46.3, Fe_2O_3 = 7.6 T2: MgO = 44.3, Fe_2O_3 = 12.1	Distilled water	$P_{CO2} = 10$ bar, $T = 32–40$ °C, time = 6 h, p. size = 67 μm $P_{CO2} = 8$ atm, T = 32–40 °C, time = 6 h, p. size = 47 μm solid/liquid ratio = 150 g/l, gas/liquid ratio = 3, stirring speed = 600 rpm	T1 = 8.5 % T2 = 10.8 %	T1 = 0.22 g CO_2/g T2 = 0.25 g CO_2/g	Kemache et al., 2017	MC under original mild conditions; transition from a laboratory to a pilot scale requires some adjustments to improve process efficiency; heat-treatment and carbonate precipitation.
Ultramafic nickel ores	MgO = 45.8	Distilled water 1 M NaCl + 0.64 M $NaHCO_3$	$P_{CO2} = 124$ bar, $T = 155$ °C, time = 1 h, Solid/liquid ratio = 20 % stirring speed = 1000 rpm	36.6 %	18.3 g CO_2/100 g	Bobicki et al., 2015	Types of industrial wastes for mineral carbon sequestration and the process routes.
Steel slag	CaO = 34–45	Millipore water	$P_{CO2} = 1$ bar, flow rate = 30 cm^3/min $T = 90$ °C, time = 240 h p. size <25–37 μm	70 %	–	Yadav and Mehra, 2017	Significant degree of carbonation achieved under mild conditions; concentration of toxic mineral ions remained within the prescribed limit during carbonation.

*Limited to aqueous MC; E_{CO2} – Carbonation efficiency.

(*continued on next page*)

Table 2 (*continued*)

Feedstock material	Metal oxide (%)	Solution	Operating conditions	E_{CO2}	CO_2 capture	Reference	Remarks
			stirring speed = 700 rpm				

*Limited to aqueous MC; E_{CO2} – Carbonation efficiency.

Feedstock material	Metal oxide (%)	Solution	Operating conditions	E_{CO2}	CO_2 capture	Reference	Remarks
Steel Slag	CaO = 42.5	Distilled water	P_{CO2} = 30 bar, T = 50 °C, time = 48 h, p. size <10 μm, stirring speed = 60 rpm Liquid/solid ratio = 1	8.8 %	29.47 g CO_2/kg	Ukwattage et al., 2015	Manipulation of water-to-solid mix ratio and the reaction temperature to enhance carbonation reaction.
Steel slag	CaO = 33.19 Fe_2O_3 = 38.19	Distilled water	P_{CO2} = 10.69 bar, T = ambient, time = 10 min, p. size<67 μm Liquid/solid ratio = 10, gas/liquid ratio = 3, stirring speed = 600 rpm	–	0.052 g CO_2/g	Ghacham et al., 2016	Carbonation efficiency of steel slag carbonation in slurry phase under ambient temperature.
EAF Steel slag	CaO = 28.27 Fe_2O_3 = 24.25	Distilled water	P_{CO2} = 6 bar, T = 30 °C, time = 3 h, p. size <2 mm, stirring speed = 500 rpm Liquid/solid ratio = 10	27 %	82 g CO_2/kg	Revathy et al., 2016	Direct MC at room temperature and low-pressure conditions.
BOF Steel slag	CaO = 52.82	Distilled water	P_{CO2} = 48.26 bar, T = 160 °C, time = 12 h, p. size <44 μm, Liquid/solid ratio = 10 ml/g	68.3 %	283 g CO_2/kg	Chang et al., 2012	Accelerated carbonation in a high-gravity rotating packed bed is method due to high mass-transfer rate.

NA: *Limited to aqueous MC; E_{CO2} – Carbonation efficiency.

Feedstock material	Metal oxide (%)	Solution	Operating conditions	E_{CO2}	CO_2 capture	Reference	Remarks
Carbide slag Waste lime Steel slag Waste concrete	CS: CaO = 69.19 MgO = 1.10 WL: CaO = 81.32 FeO = 0.34 SS: CaO = 38.91 Fe_2O_3 = 23.11 FeO = 21.62 MgO = 7.61 WC: CaO = 23.51 Fe_2O_3 = 1.12 MgO = 1.64	Distilled water + 1.67 M Na_2SiO_3 + 0.84 M NH_4Cl	P_{CO2} = 10 bar, T = 55 °C, time = 125 min, p. size = 74–150 μm, Liquid/solid ratio = 6	CS = 64 % WL = 72 % SS = 52 % WC = 32 %	CS = 0.4428 kg CO_2/kg WL = 0.5855 kg CO_2/kg SS = 0.2023 kg CO_2/kg WC = 0.0752 kg CO_2/kg	Chang et al., 2015	Products of carbonation (solid residues) were more suitable to manufacture artificial aggregate with higher strength.
Diamond tailings, red mud, coal ash	CaO = 1.80–6.48	Distilled water	T = 300–450 °C, time = 1–2 min, p. size 300–600 μm	–	0.76–0.89 mg CO_2/g	Coppola et al., 2022	Viability of recycling mining waste via direct MC with an appreciable CO_2 capture capacity at low range temperature.
Mine tailings	CaO = 13.55 MgO = 13.90 Fe_2O_3 = 6.78	Deionized water	P_{CO2} = 1 bar, T = 22 °C, p. size<100 μm flow rate = 200 ml/min	1 %	1.79 kg CO_2/kg	Woodall et al., 2021	Carbon mineralization at ambient temperature and pressure with elevated CO_2 concentration.

*Limited to aqueous MC; E_{CO2} – Carbonation efficiency.

and suitability to be used in CBM for CO_2 capture. From current related studies, the CaO, MgO and Fe_2O_3 content of these admixtures are between 0.81–61.2 %, 0.3–95.8 % and 0.1–27.4 %, respectively, which correspond to 8–46 % of CO_2 uptake capacity (average of 20.6 %). Therefore, it is important to consider the mineralogical characteristics of the admixtures that may have influence on carbonation reaction and capacity for CO_2 capture.

The reported CO_2 uptake of the CBM were; 5.4–20 % (concrete or cement mortar), 17–35 % (concrete blocks/bricks), 23–28 % (cement fiber boards), 11 % (reinforced concrete) and 29.6–46 % (engineered cementitious composites). CO_2 capture for in-situ application in coal mining goaf backfilling has been estimated to be between 25 and 43.75

Table 3
Influencing factors for indirect mineral carbonation utilizing natural minerals and industrial waste.

Feedstock material	Metal oxide (%)	Solution	Operating conditions	E_{CO2}	CO_2 capture	Reference	Remarks
Wollastonite	CaO = 46.06	Distilled water, Sulfuric acid (H_2SO_4) 10 % ammonia	P_{CO2} = 1 bar, T = 30 °C, p. size<20 μm stirring speed = 600 rpm flow rate = 40 ml/min, time = 1 h	91 %	–	Ding et al., 2014	High carbonation rate obtained with sulfuric acid and ammonia at normal atmospheric pressure.
Coal fly ash	CaO = 7.2 MgO = 1.5 Fe_2O_3 = 7.8	Deionized water	P_{CO2} = 1 bar, T = 25 °C, p. size<20 μm stirring speed = 700 rpm flow rate = 2 ml/min, solid/liquid ratio = 100 g/l	10 %	0.11 g CO_2 /g	Jo et al., 2012	Carbonation under ambient pressure and temperature without chemical extractant.
Waste cement material	CaO = 3.4 MgO = 1.2 Fe_2O_3 = 0.9	Ammonium acetate (CH_3COONH_4), ammonium chloride (NH_4Cl), ammonium nitrate (NH_4NO_3), and ammonium sulfate $(NH_4)_2SO_4$)	P_{CO2} = ambient, T = ambient, pH = 9.5–10.5 stirring speed = 300 rpm flow rate = 40–200 ml/min solid/liquid ratio = 50 g/l	20–60 %	0.18 g CO_2/g	Jo et al., 2014	Ammonium acetate and ammonium nitrate are effective solvents under ambient pressure and temperature.
Red gypsum	CaO = 32.2 Fe_2O_3 = 28.99	Sulfuric acid (H_2SO_4), ammonium hydroxide (NH_4OH)	P_{CO2} = 1–70 bar, *T* = 25 °C, p. size<38 μm stirring speed = 1000 rpm time = 30–90 min	Ca = 54.1–100 % Fe = 59.45–68.1 %	–	Azdarpour et al., 2015	Feasibility of pH swing process; maximum efficiency (100 %) was achieved when 8 bar CO2 pressure was used.
Olivine, synthetic magnesia	O: CaO = 2.16 MgO = 35.57 Fe_2O_3 = 10.88 M: CaO = 0.75 MgO = 97.56 Fe_2O_3 = 0.58	Sodium hydrogen carbonate ($NaHCO_3$), oxalic acid ($H_2C_2O_4$), ascorbic acid ($C_6H_8O_6$)	P_{CO2} = 117 bar, *T* = 175 °C, p. size<20–200 μm time = 4 h, solid/liquid ratio = of 1:15 and 1:5	95 %	–	Stopic et al., 2018	Formation of magnesium carbonate under high pressure and temperature; small content of cobalt and chromium after carbonation.
Red gypsum	CaO = 33.12 Fe_2O_3 = 29.23	Sulfuric acid (H_2SO_4), mono-ethanolamine (MEA)	P_{CO2} = 200 bar, *T* = 315 °C, p. size<38 μm stirring speed = 600 rpm	20–90 %	–	Rahmani, 2020	Use of different concentrations of extractants; 1.4 M MEA could absorb the highest amount of CO2 to precipitate the calcite.
Iron-rich mining waste	CaO = 8.21 MgO = 9.30 Fe_2O_3 = 22.90	Ammonium sulfate ($(NH_4)_2SO_4$), ammonium chloride (NH_4Cl), ammonium acetate (CH_3COONH_4), ammonium bisulfate (NH_4HSO_4), sulfuric acid (H_2SO_4), 2,2′-bipyridine, $[Fe(bipy)3]^{2+}$	P_{CO2} = 1 bar, T = 20–80 °C, p. size<68 μm pH 12	56 %	0.11 kg CO_2/kg	Reynes et al., 2021	pH-swing approach by cation complexation; use of mild temperature and pressure conditions to obtain iron carbonates.
Coal fly ash	CaO = 3.44 MgO = 0.82 Fe_2O_3 = 3.13	HNO_3, Na_2CO_3, NaOH, bipolar membrane electrodialysis (BPED)	p. size<20 μm stirring speed = 400 rpm flow rate = 1000 ml/min	92 %	0.011 g-CO_2/g	Ho et al., 2022	Circular indirect carbonation with bipolar membrane electrodialysis (leaching, CO_2 capture, calcium carbonate precipitation, liquor purification and regeneration of acid and alkaline solution.)

*Limited to aqueous MC; E_{CO2} – Carbonation efficiency.

*Limited to aqueous MC; E_{CO2} – Carbonation efficiency.

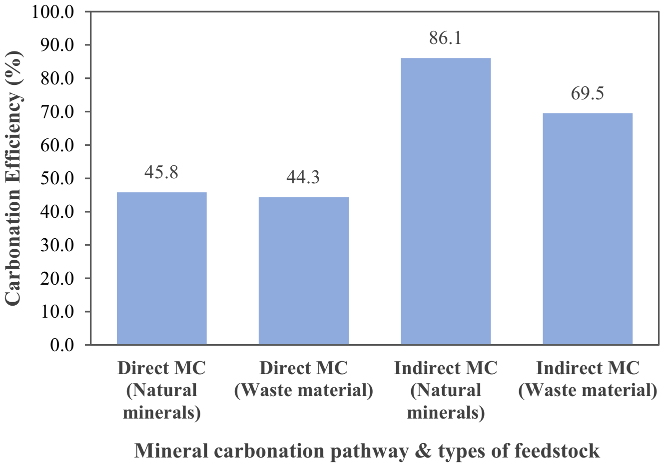

Fig. 6. Carbonation efficiency comparison between direct and indirect mineral carbonation using natural minerals and waste materials as feedstock.

% (Wang et al., 2019). The equivalent CO_2 capture of MOC boards was estimated at about 147 kg CO_2/t board/ year with carbonation curing (Power et al., 2017). In most studies, pure CO_2 gas (>99 %) was used to simulate CO_2 capture during carbonation curing, thus giving the maximum potential of sequestration and strength attainment.

Early carbonation curing (pre-carbonation hydration) is important to increase the hydration process and strength of carbonated products (El-Hassan and Shao, 2014; Abdul-Baki, 2017), and is a novel parameter for managing the curing process. With pre-carbonation hydration, the carbonation of hydration products is particularly important since bound water content decreases during carbonation, allowing for more strength development (Zhang et al., 2020). A longer pre-curing and carbonation time resulted in higher compressive strength, e.g. 16.9 % increase in cement mortar (Chen and Gao, 2019). The CO_2 uptake rate often increases within the first few hours of carbonation, however high CO_2 pressure (> 100 kPa) is needed for early carbonation curing, which requires high costs to be applied at the industrial scale (Abdul-Baki, 2017). Nevertheless, a recent study suggested that carbonation curing at ambient pressure has comparable performance as those at high pressure (Xian et al., 2022). It has been noted that a longer pre-carbonation hydration, i.e. 71 h has resulted in the highest 28-d compressive strength of cement mortar, having risen by 38–53 % from non-carbonated material (Zhang et al., 2020). From the current review, a pre-carbonation time between 3 and 71 h have been applied, where 18-24 h pre-carbonation curing is mostly adopted.

Similarly, the corresponding CO_2 capture is influenced by the carbonation curing at a range of exposure time. Regardless of the CBM types, CO_2 uptake is seen to be increasing with the increase of carbonation time (Fig. 7). Statistical correlation supports the relationship between CO_2 uptake and carbonation time with ($r = 0.55$; $p < 0.01$). Examples from concrete block application indicated an exposure from 4 h to 4d on CO_2 curing following an 18 h pre-carbonation curing, resulting in 12 % increase of CO_2 capture (El-Hassan and Shao, 2014). A increased sequestration rate of 12 % was achieved in engineered cementitious composites when carbonation was extended from 24 h to 7d (Wu et al., 2018), and 5 % increase when carbonation was prolonged from 2 h to 24 h for cement fiberboards (He et al., 2019). In cement mortar application, extending carbonation time from 2 h to 14d following the 12-24 h pre-carbonation curing has slightly improved CO_2 uptake by 2.2 % (Mo et al., 2019). Overall, it has been found that an average of 20.6 % of CO_2 capture per unit material can be achieved with carbonation curing (under various experimental conditions) from as early as 2 h to 14d. Therefore, continuous curing and prolonged carbonation time are required to increase the CO_2 reaction and to improve the strength of concrete products. While it is understood that longer carbonation will increase CO_2 uptake, it is limited to 24 h to be economical (El-Hassan and Shao, 2014; He et al., 2019).

Carbonation curing has an important role in material strength development. The strength of concrete mortar has increased to between 51 and 119.5 MPa compared to the base case with steam curing (Mo et al., 2017, 2019; Huang et al., 2019; Qin et al., 2019; Alimi et al., 2022). The 28-d compressive strength was also improved in concrete blocks, i.e. 17.3–26.7 MPa with 15.5 % increase from non-carbonated specimen (Ghouleh et al., 2017). Fig. 8 depicts the compressive strength by type of CBM as influenced by carbonation time. Nevertheless, there is no clear relationship between compressive strength and carbonation time among different CBMs ($p > 0.05$). Despite this, a longer carbonation time (24 h) applied for engineered cementitious composites and cement fiberboards has produced acceptably high compressive strength between 31 and 54 MPa. However, shorter exposure times of 2-4 h have been able to promote high-strength cement mortar, i.e. 51–80 MPa. A 61 MPa strength has been achieved in reinforced concrete under 12 h exposure with carbonation curing. The exceptionally high strength of cement mortar used in Huang et al. (2019) is because of the use of natural minerals, i.e. wollastonite as the admixture to OPC, while others are using industrial waste materials. It should be noted that the role of post-carbonation hydration is similarly important as the pre- and carbonation phase for complete strength attainment (Zhang et al., 2020, 2021; Xian et al., 2022).

Another important factor in carbonation curing is the water content, where 40–60 % is the ideal range to increase the carbonation reaction (He et al., 2019). Other researchers indicated that the ideal water loss of cement paste for CO_2 uptake is between 30 and 40 % (Chen and Gao, 2019), while 50 % is the optimum water loss of the total water content of carbonated specimens (Abdul-Baki, 2017). If there is too much water, the carbonation reaction would be reduced because it prevents the diffusion of capillary pores and CO_2 through the concrete (Chen and Gao, 2019; Zhang et al., 2017). Different pre-curing cycles of carbonated specimens prove that higher water loss facilitates greater CO_2 uptake (Zhang et al., 2017). Thus, water content plays an important role in carbonation curing to enhance the CO_2 uptake in concrete products. Other conditions such as water-binder ratio, sample porosity, CO_2 pressure and additive (forming agent) also have influence on carbonation reaction and have been reviewed in Wang et al. (2019). Overall, it has been projected that utilization of CO_2 curing in all CBM generated worldwide (concrete blocks, concrete pipes, ceramic bricks, concrete paving blocks and cement-bonded particleboards) would lead to a 22 % reduction in cement-related CO_2 emissions (El-Hassan, 2020).

4.4. Mining waste as feedstock in carbon capture, utilization and storage

4.4.1. Mineral availability in mining waste

While mining waste is considered non-economical, it can be recovered as feedstock for MC due to the presence of silicate minerals and its abundance at numerous mining sites across the globe. It also has been learned from earlier analysis (Section 4.1) that mining waste is greatly produced globally and has the highest sequestration capacity among other waste types. Mining wastes are produced in the form of rocks or solid (e.g. waste rock, overburden, gangue and tailings) and liquid (e.g. mine water and sludge). They can be found in active or abandoned mines within a mining pit, waste dump, spoil heap, stockpile, tailings pond or storage facility, which signify complex geotechnical constructions (Hitch et al., 2010). Regardless of the types and forms of mining waste, mineral availability and the nature of mining waste (i.e. acidic or alkaline) are the key considerations to determining the options for MC adoption (Fig. 9).

Among the types of mine waste, tailings have more potential for carbonation. As mine tailings contain water in it, the demand for water in aqueous MC can be eliminated (Ebrahimi et al., 2017). However, the term mine tailings sometimes refers to the solid-type mining waste such as the gangue and waste rocks, which are regarded as any waste or

Table 4
Carbonation curing adoption and resulting CO_2 capture capacity.

Type of waste/admixture	Type of CBM	Mineral composition of admixture	Compressive strength	CO_2 capture capacity	Carbonation/hydration time	Reference
Steel slag	Concrete	CaO 42.42 %; MgO 7.19 %; Fe_2O_3 27.37 %	61.3 MPa (14d CO_2 curing; 60 % SS; 18 h hydration +14d carbonation)	–	–	Mo et al., 2017
Wollastonite	Cement mortar	CaO 42.79 %; Fe_2O_3 3.37 %	80 MPa (0.5–2.5 MPa, 2 h curing)	20 %	2 h carbonation	Huang et al., 2019
Magnesium slag	Calcium carbonate binders	CaO 53.86 %; MgO 7.24 %; Fe_2O_3 8.17 %	119.5 MPa (14d CO_2 curing)	13.4–15.6 %	24 h pre-carbonation hydration +1–14d carbonation	Mo et al., 2019
Limestone powder (LP), fly ash (FA) and ground granulated blast-furnace slag (GGBS)	Cement mortar	LP: CaO 56.1 %; MgO 0.41 %; Fe_2O_3 0.15 % FA: CaO 11.53 %; MgO 1.13 %; Fe_2O_3 9.47 % GGBS: CaO 48.68 %; MgO 3.91 %; Fe_2O_3 0.90 %	51, 56, 53 MPa for LP, FA and GGBS, respectively (28d)	10.42, 13.94, 11.60 % for LP, FA and GGBS, respectively	24 h pre-carbonation hydration +4 h carbonation	Qin et al., 2019
Brick kiln dust	Cement mortar	CaO 36.6 %; MgO 0.26 %; Fe_2O_3 2.18 %	–	8–14 %	12–18 h pre-carbonation hydration +12 h carbonation	Alimi et al., 2022
Portland limestone cement	Cement mortar	CaO 60.8 %; MgO 2.4 %; Fe_2O_3 2.4 %	19–29 MPa (28d)	5.4–6.1 %	71 h pre-carbonation hydration	Zhang et al., 2020
Steel slag	Concrete masonry blocks	CaO 61.21 %; MgO 4.89 %; Fe_2O_3 3.04 %	17.3–26.7 MPa (28d)	17–20 %	18 h pre-carbonation hydration +2 h carbonation	Ghouleh et al., 2017
–	Concrete blocks	–	–	22–24 % 35 %	4 h carbonation 18 h pre-carbonation hydration +4d carbonation	El-Hassan and Shao, 2014
Cellulose fibers	Cement-bonded fiberboards	–	23.1 MPa (28d)	23–28 %	18 h pre-carbonation hydration +2–24 h carbonation	He et al., 2019
Light-burned MgO, fly ash	Engineered cementitious composites	MgO 95.76 %; CaO 0.81 %; Fe_2O_3 0.13 %	31.5–41.9 MPa (7d)	34–46 %	3 h pre-carbonation hydration +1–7d carbonation	Wu et al., 2018
Fly ash	Engineered cementitious composites	CaO 3.4 %; MgO 0.9 %; Fe_2O_3 13.5 %	36.1–54 MPa (28d)	29.6–35.1 %	3 h pre-carbonation hydration +24 h carbonation	Zhang et al., 2021
–	Reinforced concrete	–	61.5 MPa (28d)	11 %	6 h pre-carbonation hydration +12 h carbonation	Xian et al., 2022
–	Cementitious backfilling material	–	–	25–43.75 %	48 h carbonation	Wang et al., 2019
–	Magnesium oxychloride cement (MOC) boards	–	–	9.8 kg CO_2/t board/ year 147 kg CO_2/t board/ year	passive rate accelerated rate	Power et al., 2017

"–" – information not available/reported.

unwanted materials of no or less value that are produced from mining activities.

Rock waste is a coarse material with varying particle sizes that is produced during mineral mining with overburden and typically has minimal mineral value (Harrison et al., 2013; Makoundi et al., 2014; Zarandi et al., 2017). In carbon sequestration, rock wastes from ultramafic-hosted ore deposits are typically favoured for carbon mineralization because of the presence of Mg-silicates in end product of mining activities and it also holds basic ultramafic minerals like lizardite ($Mg_3Si_2O_5(OH)_4$, olivine (Mg_2SiO_4), and weathered minerals like serpentine ($Mg_3(OH)_4(Si_3O_5)$) (Li and Hitch, 2015). Magnesium and lizardite carbonates will be formed when olivine reacts with CO_2 and water as shown in reaction 12, whereas lizardite subsequently reacts with CO_2 to generate quartz (SiO_2) and magnesite ($MgCO_3$) in reaction 13 (Manning and Renforth, 2012; Renforth et al., 2011). These Mg-silicate carbonation processes result in a stable carbonate.

$$2Mg_2SiO_4 + CO_2 + 2H_2O \rightarrow Mg_3Si_2O_5(OH)_4 + MgCO_3 \quad (12)$$

$$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O \quad (13)$$

In addition, conversion of Ca and Mg-silicate minerals to carbonates involves significant change in volume during carbonation reaction. For example, the reaction of olivine with aqueous CO_2 produces magnesite and quartz as shown in reaction 14, while reaction of larnite (Ca_2SiO_4) with aqueous CO_2 yields the final products of calcite ($CaCO_3$) and quartz (reaction 15). In this reaction, the change in volume for substitution of Mg-olivine by magnesite in reaction 14 is about 23 % if silica concentrations are preserved under quartz saturation (Gras et al., 2017).

$$Mg_2SiO_4 + 2CO_2\ (aq) \rightarrow 2MgCO_3 + SiO_2 \quad (14)$$

$$Ca_2SiO_4 + 2CO_2\ (aq) \rightarrow 2CaCO_3 + SiO_2 \quad (15)$$

In rock weathering, wollastonite ($CaSiO_3$) minerals are formed during the carbonation process of Ca-silicates in metamorphic rocks, which can boost the uptake of carbon as shown in reaction 16 (Manning and Renforth, 2012; Qafoku, 2014; Renforth, 2019).

$$CaSiO_3 + CO_2 + 2H_2O \rightarrow CaCO_3 + H_4SiO_4 \quad (16)$$

Table 5 provides some examples of the chemical composition and

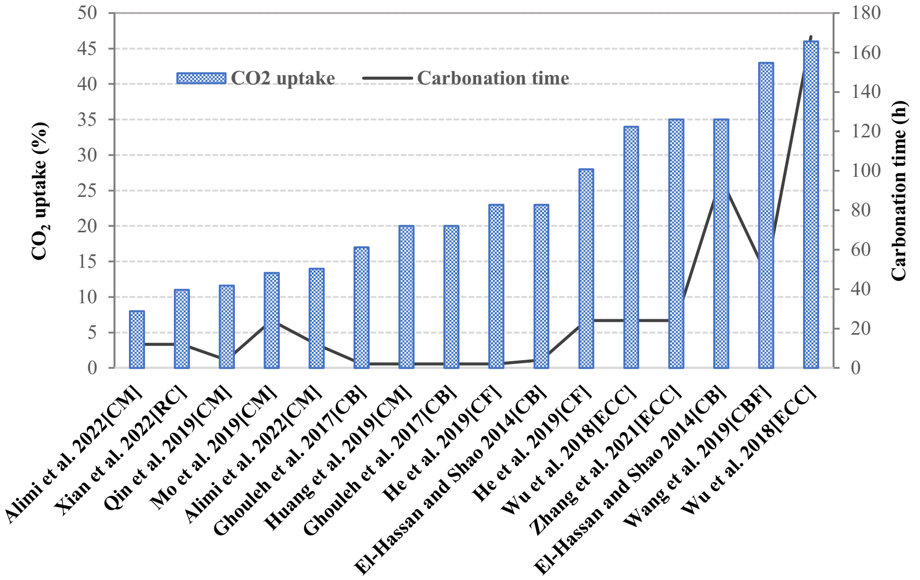

Fig. 7. CO_2 uptake of cement-based materials in relation to carbonation time for CM (concrete mortar), RC (reinforced concrete), CB (concrete blocks), CF (cement fiberboards), ECC (engineered cementitious composites), CBF (cementitious backfilling material).

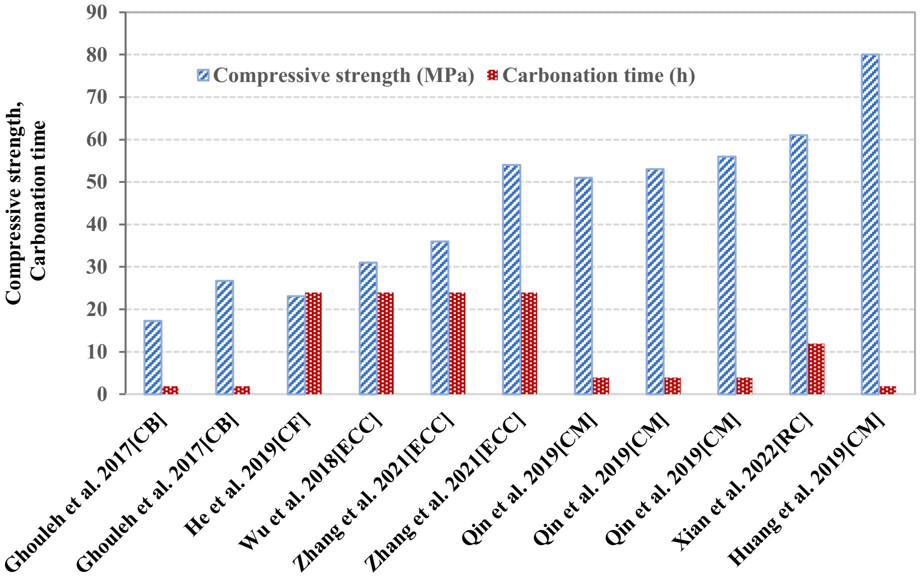

Fig. 8. Compressive strength of cement-based materials as influenced by carbonation curing in CB (concrete blocks), CF (cement fiberboards), ECC (engineered cementitious composites), CM (concrete mortar) and RC (reinforced concrete).

mineralogy of mining waste for carbon sequestration. Recent research have explored mining waste potential from metal and non-metal mining such as iron ore, gold and limestone, and discovered availability of Ca-Mg-Fe-silicate minerals which makes it favourable for carbonates production (Hasan et al., 2018; Molahid et al., 2023). The proportion of CaO (0.1–71.6 %), MgO (1.7–21 %) and Fe_2O_3 (3.2–71.9 %) greatly differs according to the type of mineral commodity, suggesting more complex mechanisms of sequestration while offering more utilization potential of the captured carbon. The large variations of the mineral composition suggest that specific type of mineral commodity (targeted waste material) may be suited for an intended sequestration application. For example, a greater amount of CaO (~72 %) was found from limestone waste, while bauxite residue contributed up to 21 % MgO. Large amount of Fe_2O_3 (~70 %) was mainly sourced from bauxite and iron ore residues. Notably, Fe oxide is another important mineral for carbonation alongside Mg and Ca oxides, however less research has used Fe oxide for MC because it is a vital mineral resource for various applications (Jacobs, 2014). More recent studies have discovered the role of Fe oxide that can facilitate carbonation, and there is opportunity for carbonate regeneration from the mineral reactions (Mendoza et al., 2019a, 2019b). Inherently, Fe oxide is seen as a new prospect in mining waste utilization as an efficient sorbent for CO_2 capture in which carbonation can be achieved at an ambient temperature and CO_2 pressure of 10–30 bar (Mendoza et al., 2019b). Sequestration of Fe oxides has been observed under low-reaction conditions (80 °C, ambient CO_2 pressure) of a direct aqueous MC resulting in total carbonation efficiency of ~11 % (Ramli et al., 2021; Kusin et al., 2023). Therefore, understanding the nature of the mine waste is greatly important so that suitable processes can be designed to enhance carbonation reaction efficiency. Utilization of mining waste is advantageous with more insights into various mechanisms facilitating CO_2 capture due to a variety of potential minerals.

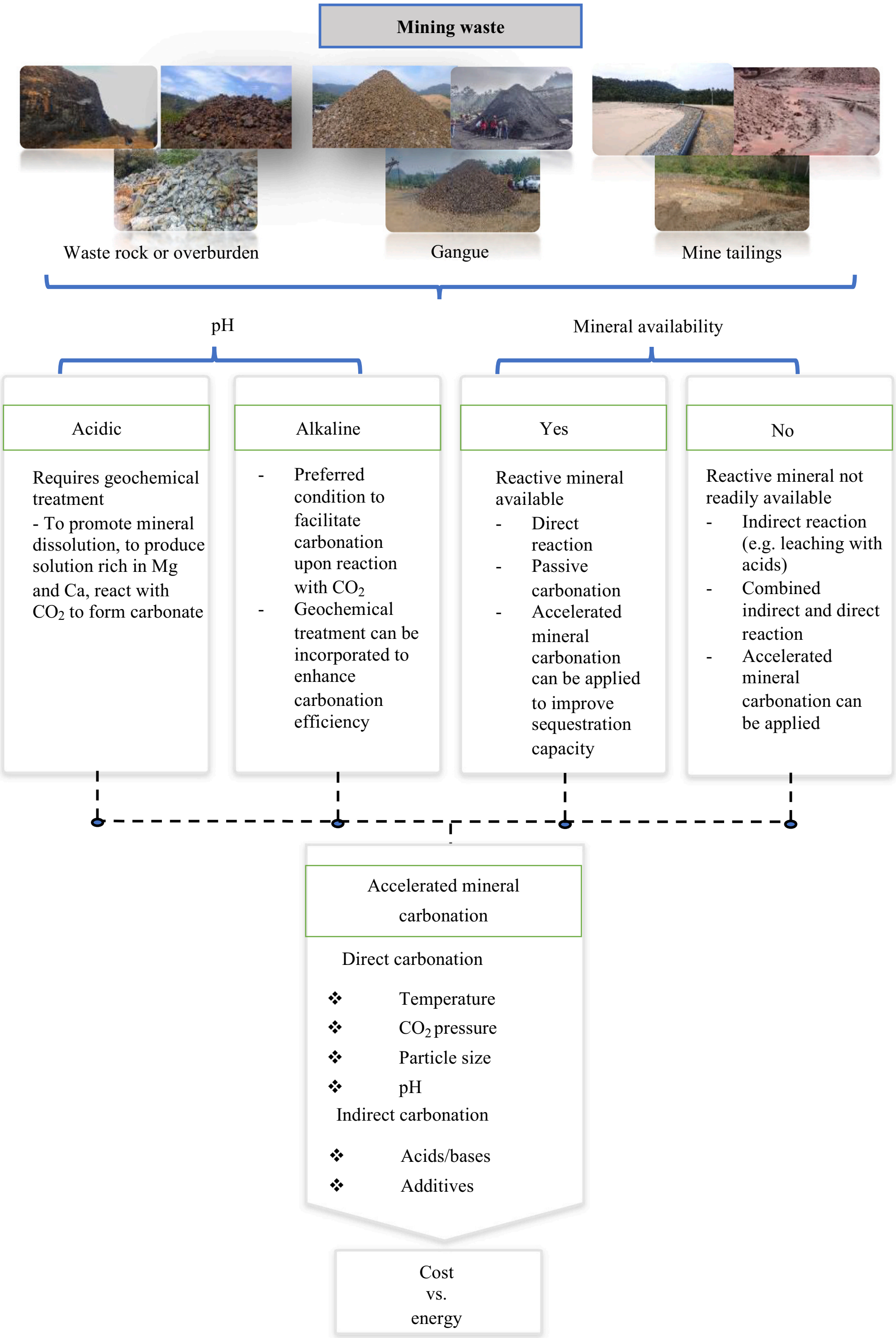

Fig. 9. Synthesis of key considerations for mining waste utilization through mineral carbonation. Accelerated mineral carbonation is suggested to improve carbonation efficiency but implications on the costs and energy use should be considered.

4.4.2. *Mining waste utilization in carbon capture, utilization and storage technology*

Combination of mining operations and MC has been an interesting option providing opportunities for recovery applications and innovations (Li et al., 2018). Utilization of mining waste as carbonates and value-added products from the carbonation process, may be useful for permanent CO_2 storage in the production of green material.

Fig. 10a visualizes how mining waste can be utilized in MC technology in the context of in-situ and ex-situ applications. The in-situ MC includes CO_2 injection into the mine tailings (active) or by means of a natural (passive) CO_2 sequestration in the vicinity of the mine site, with the purpose of permanently storing the captured CO_2. Whereas, ex-situ MC takes place outside or nearby the mine site, which consumes silicate-containing minerals as the sequestering agent for permanent storage or production of new materials. For ex-situ MC, the carbonates product can be utilized for various uses, e.g. construction and

Table 5
Mineralogy and chemical composition of mining waste for carbon sequestration.

Mining waste type	Example mineral component	Chemical formula	Estimated divalent cation for carbonation (MgO, CaO, Fe_2O_3)[a]	Reference
Iron ore mining waste	Siderite	$FeCO_3$	67.3 % Fe_2O_3	Sara et al., 2010
	Goethite	$HFeO_2$	6.2 % CaO	Assima et al., 2014
	Hematite	Fe_2O_3	2.7 % MgO	Bodénan et al., 2014
	Magnetite	Fe_3O_4		Sarvaramini et al., 2014
	Pyrite	FeS_2		Ramli et al., 2021
	Ilmenite	$FeTiO_3$		Molahid et al., 2022
	Quartz	SiO_2		
	Chamosite	$(Mg,Fe,Al)_6(Si,Al_{)}{}_{414}(OH)_8$		
Bauxite residue	Calcite	$CaCO_3$	40 % CaO	Gräfe and Klauber, 2011
	Gypsum	$CaSO_4.2H_2O$	21 % MgO	Renforth, 2019
	Chrysotile	$Mg_3(Si_2O_5)(OH)_4$	71.9 % Fe_2O_3	Swain et al., 2011
	Brucite	$Mg(OH)_2$		Lechat et al., 2016
	Talc	$Mg_3(SiO_5)_2(OH)_2$		Harrison et al., 2013
	Chlorite	$(Mg,Fe,Al)_{6(}Si,Al)_4O_{10}(OH)_8$		
	Chantalite	$CaAl_2SiO_4(OH)_4$		
	Chamosite	$(Mg,Fe,Al)_6(Si,Al_{)}{}_{414}(OH)_8$		
	Boehmite	$Al_2O_3{\bullet}H_2O$		
	Gibbsite	$Al_2O_3{\bullet}3H_2O$		
	Kaolinite	$Al_2O_3.2SiO_2.2H_2O$		
	Quartz	SiO_2		
	Wustite	FeO		
	Hematite	Fe_2O_3		
	Magnetite	Fe_3O_4		
	Goethite	$HFeO_2$		
	Hydrogarnet	$Ca_3AlFe(SiO_4)(OH)_8$		
	Phlogopite	$KMg_3(Si_3Al)O_{10}(OH)_2$		
	Cancrinite	$Na_6CaAl_6Si_6(CO_3)O_{24}.2H_2O$		
	Albite	$NaAlSi_3O_8$		
Gold mining waste	Quartz	SiO_2	1.7 % MgO	Assima et al., 2014
	Chlorite	$(Mg,Fe,Al)_{6(}Si,Al)_4O_{10}(OH)_8$	3.2 % Fe_2O_3	Roussel et al., 2000
	Feldspar	$KAlSi_3O_8$ – $NaAlSi_3O_8$ – $CaAl_2Si_2O_8$	0.1 % CaO	Kusin et al., 2023
	Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)$		
	Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$		
	Muscovite	$KAl_2(AlSi_3O_{10})(F,OH)_2$		
	Scorodite	$FeAsO_4{\bullet}2H_2O$		
	Pyrite	FeS_2		
	Arsenopyrite	FeAsS		
	Beudantite	$PbFe_3(AsO_4)(SO_4)(OH)_6$		
	Galena	PbS		
Limestone waste	Calcite	$CaCO_3$	71.6 % CaO	Renforth, 2019
	Dolomite	$CaMg(CO_3)_2$	2.8 % MgO	Mohd-Isha et al., 2021
	Quartz	SiO_2		

[a] Given as the mean data from reported values in the literature.

manufacturing purposes, or reclaiming back its residues (Ibrahim et al., 2019; Olajire, 2013; Gras et al., 2017). This concept shows more utilization potential through the ex-situ method for new materials production.

The utilization of mining waste, which has been shown to be capable of sequestering CO_2, can be regarded as a feasible approach that will benefit both the mining industry and the environment. Clearly, mining waste sequestration via CCUS can be an advantageous solution for long-term CO_2 capture, while producing revenue-generating products that benefit both the mining and construction industries. The overall concept of CCUS with integration of mining waste is illustrated in Fig. 10b, showing synergies between CCS and CCU. By this approach, it offers more opportunity for waste recovery and utilization of the captured CO_2 into usable materials or products through the coupled accelerated MC and carbonation curing. This can be achieved by carefully considering the various factors that will influence adoption of MC or carbonation curing using the waste material.

4.5. *Economic versus environmental challenges*

4.5.1. *Cost estimates for mineral carbonation*

Accelerated MC process and carbonation curing using mining waste has with it economic and environmental challenges. In fact, energy consumption and energy efficiency through production and operations are important aspects for consideration in large-scale implementation of many CCUS-related projects (Cao et al., 2022). The cost estimates for MC application are tabulated in Table 6 for comparison. In the IPCC Special Report on Carbon dioxide Capture and Storage, it is stated that the fixing cost of CO_2 sequestration is around USD50–100 per ton of CO_2. Based on CO_2 capture costs of USD55–112/t CO_2, the in-situ MC total cost has been calculated around USD72–129 per t CO_2 (Sanna et al., 2014). Meanwhile, the costs and energy consumption for ex-situ MC are mainly associated with the size of operating plant for MC, initial treatment requirements (e.g. thermal activation treatment, grinding of feedstock material), operating conditions (e.g. pressure, temperature), use of additives (separation of reactive elements) and discarding of the reaction products (Sanna et al., 2014).

The cost estimates specifically for accelerated MC with mine waste has not been widely reported in the literature. The economic assessment of MC integration in the mining industry has been evaluated in Hitch and Dipple (2012), in which estimated operation cost was USD82.5 per t CO_2. A direct MC with mechanical activation pre-treatment indicated that the mineral wastes derived from mining industry have potential to sequester up to 14.6 Mt. CO_2/y with the operating cost of USD104–107 per t CO_2 (Li and Hitch, 2016). The cost comparisons from other industrial waste and natural minerals could be the benchmark for MC adoption with mine waste in the long term. For instance, the expense of the direct MC method with pre-treatments for natural minerals like olivine, wollastonite and serpentine was estimated to be USD50, 90 and 210 per t CO_2, respectively (Gerdemann et al., 2007). Furthermore, the expense of the direct aqueous MC employing steel slag and concrete waste ranged from USD8–104 per t CO_2 depending on the operating circumstances (i.e. 200 °C, 20 bar, 100 % CO_2) (Huijgen et al., 2007). For direct MC of flue gas desulfurization gypsum, the cost evaluation

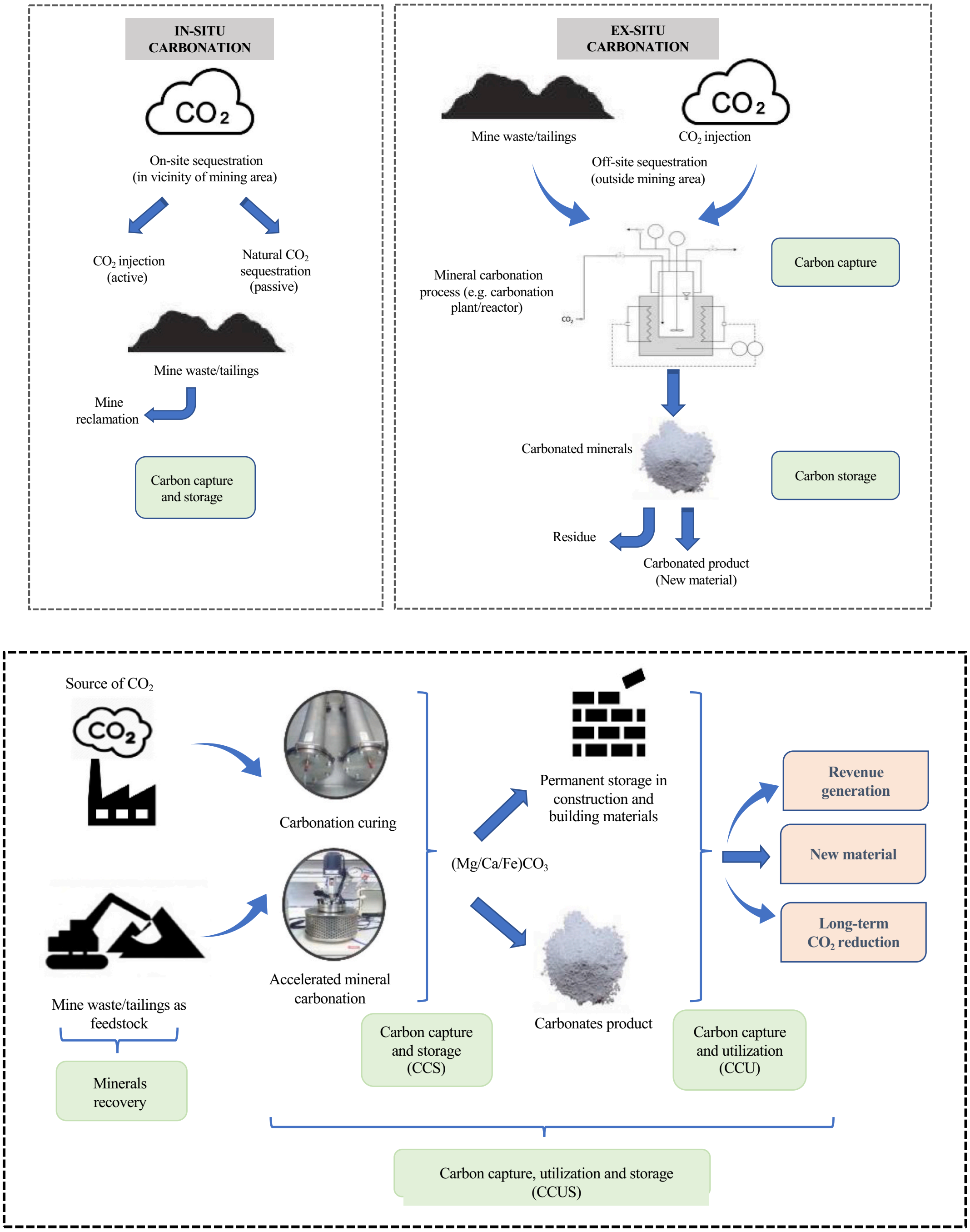

Fig. 10. (a) Illustration of in-situ and ex-situ mineral carbonation processes for carbon sequestration of mining waste (b) CCUS technology incorporating mining waste as feedstock material. This concept synergizes CCS and CCU, which offers more utilization potential of the captured carbon into usable products.

that includes the costs of output minus input materials, showed a profit of USD426.9 per t CO_2 (Altiner et al., 2019).

The total expenses of indirect MC may be more than the direct MC because of extra chemical additives, which accounts for about 43–46 % of the total expense (Rahmani et al., 2014). Other costs included energy consumption (e.g. filtration, crushing, power and heat) and transportation cost with a total of USD66.82 per t CO_2 sequestered from red gypsum (Rahmani et al., 2014). The cost of indirect MC can range between USD62 to > USD162 using natural minerals such as wollastonite and Mg-silicate (Huijgen et al., 2007). Nevertheless, the cost of the indirect carbonation in the production of high-value $CaCO_3$ and high-purity can be decreased by recovery and recycling of chemical additives in the indirect MC (Wang et al., 2021). In a CO_2 mineralization process using thermal activation of serpentine, the thermal activation, transportation of feedstocks, and carbon capture procedures were discovered to be the primary causes of CO_2 emissions and costs. However, recycling water streams and waste heat can minimize cost and energy consumption leading to a net positive carbon abatement (Khoo et al., 2021).

4.5.2. *Cost estimates for carbonation curing*

The cost implications of carbonation curing for construction industry lie in its operational process and ultimate expenditure. It has been identified that expenditure of carbonation curing can be associated with, i) necessities for energy consumption to achieve targeted material performance (CBM with optimal carbonation efficiency) and ii) costs

Table 6
Cost estimates for mineral carbonation applications with natural minerals and industrial waste.

Cost estimates	Method	Feedstock	Remarks	Reference
USD50–100 per t CO_2	–	–	Fixing cost of CO_2 sequestration	IPCC, 2005
USD72–129 per t CO_2	In-situ MC	–	Operation cost	Sanna et al., 2014
USD82.5 per t CO_2	–	–	Operation cost	Hitch and Dipple, 2012
USD104–107 per t CO_2	Direct MC	–	Operating cost	Li and Hitch, 2016
USD50, 90 and 210 per t CO_2	Direct MC	Olivine, wollastonite and serpentine	MC with pre-treatments for natural minerals	Gerdemann et al., 2007
USD8–104 per t CO_2	Direct aqueous MC	Steel slag and concrete waste	Direct aqueous MC	Huijgen et al., 2007
USD62 to > USD162	Indirect MC	Wollastonite and Mg-silicate	Operation cost	Huijgen et al., 2007
USD66.82 per t CO_2	–	Red gypsum	Energy consumption (filtration, crushing, power and heat) and transportation cost	Rahmani et al., 2014
Profit of USD426.9 per t CO_2	Direct MC	Gypsum	Flue gas desulfurization, costs of output minus input materials	Altiner, 2019

associated with the CO_2 network, which includes capture, transportation, storage and circulation (Zhang et al., 2017). The cost comparison for carbonation curing applications is given in Table 7. The technology for directly using flue gas as CO_2 source and recovering valuable by-products will greatly cut the cost. A significant component to cut the cost of carbonation curing is associated with the eventual expenses of CO_2, which was projected to be around USD15–75 per ton of pure gas collected from power plants (Xuan et al., 2016). It has been estimated that the expenditure for CO_2 capture along with the transportation of masonry blocks was USD 2.8 and 2.1 cents per unit masonry block with steam curing and carbonation curing, respectively (Mahoutian and Shao, 2016). El-Hassan and Shao (2014) reported that the cost for 4 h carbonation curing with 4 h initial curing is comparable to those with steam curing (USD 9.27 with 155 kWh compared to USD 9.84 with 164 kWh), however the cost for 18 h initial curing is too high (USD 41.74 with 696 kWh). The study suggests that the cost can be reduced without compromising the material performance by adjusting the carbonation time while maintaining >50 % water loss. Incorporation of accelerated MC in industrial waste such as steel slag for use as SCM saves about 75.8 % of the cost due to the usage of waste material, and also reduces the cost of transportation and prices of raw materials avoided (Song et al., 2021). Comparison of raw material unit price indicated much lower cost of carbonated steel slag block compared to commercial cement block (Mahoutian and Shao, 2016). The carbonated steel slag block costs USD0.37 compared to USD0.43 for a commercial cement block (Mahoutian and Shao, 2016). In terms of water consumption, carbonation curing is deemed more advantageous than steam or moist curing as the total water consumed is much lower, i.e. 0.085 m^3 per m^3 concrete compared to 1 and 3 m^3 per m^3 concrete with steam and moist curing, respectively (El-Hassan, 2020).

Table 7
Cost estimates for carbonation curing with industrial waste.

Cost estimates	Method/ material	Remarks	Reference
USD15–75 per t pure gas		Gas collected from power plants	Xuan et al., 2016
2.1 cents per unit masonry block	Carbonation curing	Expenditure for CO_2 capture including transportation cost	Mahoutian and Shao, 2016
USD 2.8 per unit masonry block	Steam curing		
USD 9.27 per m^3 concrete	Carbonation curing	Cost for 4 h carbonation curing of lightweight concrete masonry unit is comparable to steam curing 18 h initial curing incurs much higher cost	El-Hassan and Shao, 2014
USD 9.84 per m^3 concrete	Steam curing		
USD 41.74 per m^3 concrete	Carbonation curing		
USD0.37 per unit block	Carbonated steel slag block	Much lower cost of carbonated steel slag block compared to commercial cement block	Mahoutian and Shao, 2016
USD0.43 per unit block	Commercial cement block		
Saves 75.8 %	Steel slag as SCM	Cost reduction from use of waste material, cost of transportation and prices of raw materials avoided	Song et al., 2021
Economic benefits USD18.5	Concrete waste as SCM	Economic benefits per ton of concrete waste	Zhang et al., 2022

Therefore, it can be seen that generally carbonation curing of CBM may bring economic benefits and the costs are comparable to other methods of curing. The net CO_2 benefits and economic advantages from accelerated carbonation of demolition and construction waste have been studied by Zhang et al. (2022). The study concluded that only a small number of countries may achieve net zero CO_2 emissions while gaining positive economic benefits. It has been estimated that a considerably large difference was found (with CO_2 benefits ranging from 0.7 to 2.6 (ton CO_2 emission/ton CO_2 uptake), and economic benefits ranging from 18.5 to −5.6 (USD/ton concrete waste). It was suggested that the production method should be optimized to decrease avoidable emissions and maximize possible economic gains. On the other hand, it has been suggested that carbonation of industrial wastes located near or in the vicinity of CO_2 sources should be prioritized in order to minimize the expenses linked with CO_2 capture, transport and storage in CCUS deployment (Woodall et al., 2019). Among others, the most effective ways to improve economic and environmental advantages are to restructure the transport network and relocate recycling facilities (Zhang et al., 2022).

4.5.3. *Environmental challenges*

In view of the environmental aspect, the utilization of mining waste in capturing CO_2 can be considered as a useful method in solving problems associated with CO_2 emissions from a carbon intensive sector and the growing volume of accumulated residue at mining sites. Although mining waste contains important minerals for industrial uses, a substantial amount of waste generated can be utilized as a precursor for MC without the need to mine for specific minerals. By recovering mining residue as feedstock in the MC process, the area and size of waste lands may be reduced, thus lowering the environmental impact of mining operations. As environmental concerns have become more prominent, the mining sector can gain benefits from the use of its waste. Moreover, MC is regarded as a permanent and secure method of carbon disposal because the chemical reaction of CO_2 with the minerals produces a carbonate product which is not harmful to humans and the environment. This approach tackles not only the carbon emissions, but also waste generation at mining sites, which is frequently related to contamination challenges. Thus, this will help resolve environmental problems due to mining operations, which ultimately leads to the reduction of the mining industry's carbon footprint. This is also consistent with the concept of circular economy for long-term economic and environmental sustainability (Fig. 11).

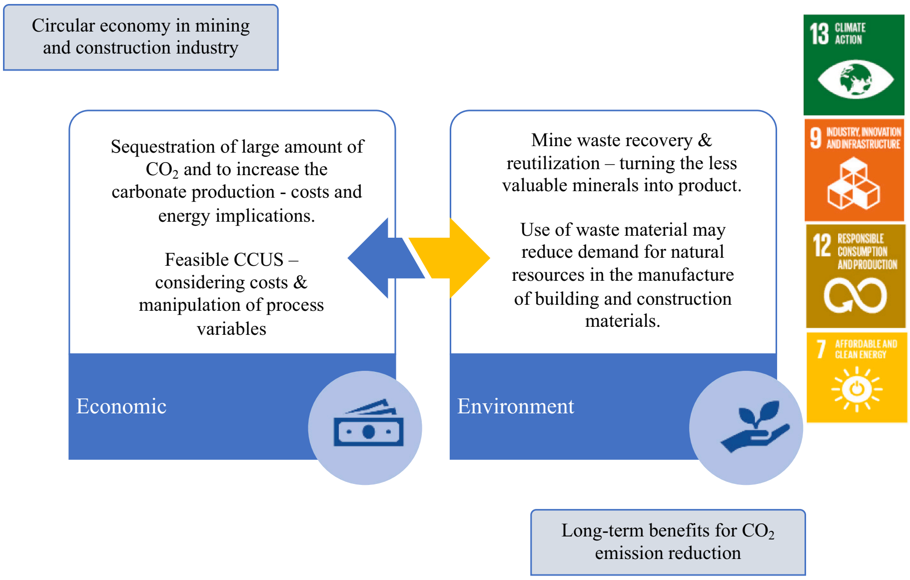

Fig. 11. Economic challenges in the adoption of accelerated MC process and carbonation curing can be offset by the environmental benefits from mining waste utilization for long-term environmental sustainability.

However, the major challenges for MC are to increase the carbonation reaction to be feasible for large-scale deployment and to minimize energy consumption. In fact, the reasons for the limitations of existing scale-up uses of CO_2 mineralization include concerns about cost and energy consumption (Liu et al., 2021). It has been known that the slow dissolution kinetics and the potentially high energy required are the main challenges to manipulate mineral processing. Furthermore, large quantities of minerals are needed for the carbonation process and to produce carbonated products. It is important that carbonates are in stable form and thermodynamically favourable to produce great sequestration capacity. To align with the net-zero emission target, it has to consider the factors that can speed up the process, which might incur some amount of costs and energy usage. Detailed evaluation of these aspects can be viewed from a life cycle assessment of competing options in CCUS deployment, and is beyond the scope of this review.

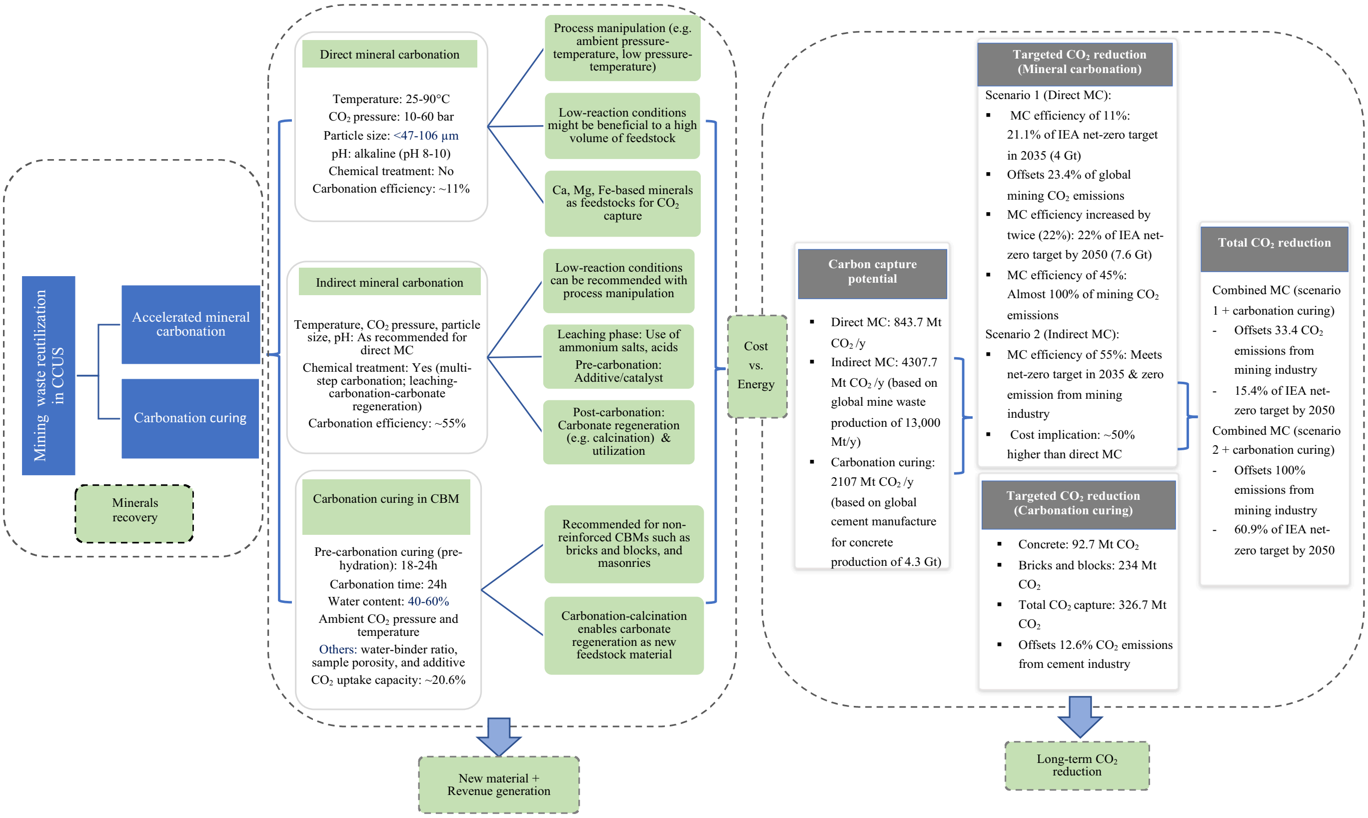

Fig. 12. Framework for mining waste utilization and considerations for an integrated CCUS adoption with long-term CO_2 reduction and new material production.

4.6. Prospects and outlook

A framework for mining waste recovery and utilization via accelerated MC and carbonation curing and important considerations for an integrated CCUS adoption is presented in Fig. 12 with the long-term CO_2 reduction targets as discussed below. This is based on the analysis of current MC efficiency and CO_2 capture capacity of these MC routes and considering the global estimates for CO_2 reduction to meet the net-zero.

4.6.1. Carbon reduction from mineral carbonation with mining waste

The abundant amount of mine waste makes it a feasible candidate for long-term carbonization through MC. From the current review, with the total global mine waste production of 13,000 Mt./y, scenario 1 (CO_2 reduction by direct MC) projects that about 843.7 Mt./y of CO_2 (30.1 % of the theoretical maximum carbonation capacity) can be sequestered based on the carbonation efficiency of 11 %. This accounts for about 21.1 % of the IEA net-zero target in 2035 (4 Gt of CO_2 capture), which can offset 23.4 % of the CO_2 emissions worldwide from mining industry, i.e. 3.5 Gt. Carbonation efficiency can be increased through accelerated MC by manipulating process variables but is constrained by the costs and use of energy. In response to the IEA scenario projection for 2050, if carbonation efficiency of direct MC can be increased by twice, e.g. ~22 %, it can reach about 22 % of the net-zero target of 7.6 Gt carbon by 2050. If carbonation efficiency reaches 45 %, this can compensate for almost 100 % of the current CO_2 emissions from the mining industry. On the other hand, scenario 2 projects that ~55 % carbonation efficiency with around 4307.7 Mt./y of CO_2 that can be captured. This will meet the net-zero target by 2035 and zero emissions from the mining industry. However, this will incur a higher cost implication by about 50 %. Note that the estimation of both scenarios are based on limited data from current reported studies on performance of direct and indirect MC processes of mine waste, and adoption of some values from global estimates and target to meet net-zero.

Thus, from the current review, it can be deduced that the options for adopting an efficient MC can be achieved through; integration of process variables (e.g. ambient pressure-temperature or low-reaction conditions), which can be implemented under the controlled environment of a carbonation plant. In cases of indirect MC, recycling of chemicals or additives might be useful for reducing the cost. As accelerated MC consumes additional energy, the quantity of CO_2 fixed is expected to be greater than the amount emitted. Nevertheless, MC can offset CO_2 emissions from industrial solid waste disposal and the production of some value-added goods, hence indirectly reducing CO_2 emissions (Liu et al., 2021). The reclamation of high-value products from the carbonation method could improve the economic benefit and make the technique more viable for industrial applications.

Availability of Fe_2O_3 provides a new prospect for mine waste utilization in MC that produces supplementary Fe-carbonate minerals alongside Ca and Mg carbonates. This highlights the opportunity for Fe-based minerals as feedstock for MC in which Fe oxides act as an efficient sorbent for CO_2 capture and can be regenerated. Carbonate regeneration through calcination is another aspect of interest to provide for more CO_2 utilization opportunities. Additionally, applications of novel catalysts for accelerated MC are also vital to reduce the overall costs (Liu et al., 2021). Again, the abundance of mine waste at numerous mining sites globally highlights its potential for future carbon reservoirs. This strengthens the need for serious deployment of CCUS in the near future to meet the net-zero emissions in 2050.

4.6.2. Carbon reduction from carbonation curing with mining waste

CCU in concrete production is estimated to sequester up to 1.4 Gt CO_2 by 2050. From the current review, with an annual global cement manufacture for concrete production of 4.3 Gt, it can be estimated that CO_2 capture from cement industry is about 2107 Mt./y (based on maximum theoretical capacity of 490 kg CO_2 capture/t cement). The global concrete production is about 30 Gt with an amount of 5–15 kg cement/(m^3 x MPa), thus it can be estimated that about 92.7 Mt. CO_2 can be captured. With current average CO_2 capture of 20.6 %, and global production of concrete blocks of 1800 Gt, it can be estimated that about 234 Mt. of CO_2 could be sequestered. Thus, the total CO_2 capture from concrete and bricks and blocks amounted to 326.7 Mt., outweighing 12.6 % of embodied CO_2 emissions from cement industry (i.e. 2580 Mt. based on IEA estimates of 0.5 t CO_2 emissions/t cement). This amount is still 4.3 times lower to reach the CO_2 reduction target in 2050 (1.4 Gt CO_2 capture by 2050).

There has been a projection that if the intended target were to be met, it is important to increase the compressive strength of concrete material from CO_2 curing and reduce electricity use from the process to gain net CO_2 benefit in concrete production (Ravikumar et al., 2021). In order to be on track with the net-zero target by 2050 scenario, the industry needs to reduce the clinker-to-cement ratio to as low as 0.5, through deployment of CCUS (IEA, 2021a). Through the use of blended cements, the clinker-to-cement ratio has declined from 0.71 in 2020 to 0.65 in 2030, and is targeted to reach 0.57 by 2050 (IEA, 2021b). On the other hand, integration of calcination into the carbonation approach provides a recycling opportunity in generating new feedstock material such as calcined-carbonated material for use as SCM. Of all CBMs, non-reinforced cementitious products have been identified as the most realistic candidates for carbonation curing in CCUS application including porous blocks and masonries as these materials possess large surface area and thin depth to facilitate CO_2 diffusion (Zhang et al., 2017).

From the perspective of CO_2 utilization, the captured carbon which is stored permanently in various types of CBMs provides opportunity for an additional revenue-generation while reducing CO_2 emissions that will benefit mining and construction industries. Clearly, waste-derived carbonated material can be produced from MC and carbonation curing and can be turned into usable or saleable products. This will give added value to the materials produced and bring revenue to the respective industries. Therefore, in order to achieve the long-term reduction target, the mining industry has to consider adopting both accelerated MC and carbonation curing wherever possible. It is projected that combined scenarios will be able to offset 33.4–100 % CO_2 emissions from mining industry, and achieve 15.4–60.9 % of IEA net-zero target by 2050. Inherently, this will help counterweight the costs associated with the capture process and other related costs along the production line which is made aligned with the circular economy.

5. Conclusions

CCUS is deemed important in putting the global energy system on a path to achieve net-zero. It can be concluded that mining waste has its dual opportunities for CCUS deployment as agent for CO_2 sequestration by means of accelerated MC and carbonation curing. The carbonation efficiency of the direct and indirect aqueous MC was estimated to be 11 % and 55 %, respectively, while CO_2 uptake capacity from carbonation curing was found to be 20.6 %. Greater opportunity can be anticipated with a better grasp of the fundamental mechanisms and factors influencing the MC. Mining waste is considered a great candidate for CCUS as it takes the advantages of its abundant amount produced and availability globally. The excessive amount of mining waste provides substantial recovery opportunity for CO_2 sequestration due to availability of divalent cations, i.e. Ca, Mg and Fe-based minerals from a range of silicate minerals. If CCUS is applied at a large scale of global mining operation, it might be useful for long-term carbonization even under low-reaction conditions. Therefore, emphasis should be given on CCU rather than CCS alone, e.g. utilization of mining waste in producing revenue-generating products, which is essentially important to counterbalance the costs linked with the process of capture and energy usage, e.g. high-reaction condition. This highlights the priority for CCUS deployment in mining, cement and construction industries in the near future to meet net-zero. At the current rate of mining waste sequestration capacity, the combined MC and carbonation curing might offset 33.4–100 % of embodied CO_2 emissions from the mining industry. Therefore, these coupled approaches are recommended which can account for about 15.4–60.9 % of the net-zero target by 2050. Note that this contribution is from mining waste utilization alone, while there still exists a range of other alkaline industrial waste similarly useful for long-term CO_2 capture.

Prospects for mining waste utilization through an integrated CCUS adoption are as follows:

- Considering process manipulation (e.g. ambient or low pressure-temperature); low-reaction conditions might be beneficial when applied to a high volume of feedstock material. This is to reduce electricity usage mainly associated with energy or power consumption to enable high-capacity CO_2 sequestration.
- Additional carbon sequestration can be attributed to the availability of Fe-based minerals alongside the commonly used Ca- and Mg-based silicate minerals. This provides new insight into sustainable utilization of mine waste-derived minerals such as from iron ore mine waste and red mud.
- Integration of carbonation-calcination process which enables carbonate regeneration as new feedstock material for MC and carbonation curing in CBM. This will optimize the utilization potential of mine waste as a sustainable feedstock material.
- Increasing the current rate of direct MC efficiency by twice will contribute to 22 % of the net-zero target by 2050, however the implications on costs and energy should be considered.
- Indirect MC provides a promising opportunity for reducing 100 % CO_2 emission and meeting the net-zero target, however the cost will be ~50 % higher than direct MC.
- Carbonation curing alone is still far (4.3 times lower) from reaching the CO_2 reduction target in the cement industry by 2050. Greater opportunity is seen for non-reinforced CBMs such as bricks and blocks, and masonries. Process manipulation in carbonation curing such as considering pre-carbonation hydration and ambient conditions (e.g. pressure and temperature) will benefit in terms of energy and associated costs.

Therefore, as CCUS forms an integral part in meeting the future target for climate mitigation actions, it should be considered an option in current and future strategies and policies to reach net-zero emissions when dealing with mining waste. Despite its technical, economic and environmental challenges, CCUS is paving way for a more sustainable global mineral resource production and in meeting the net-zero emissions.

CRediT authorship contribution statement

Faradiella Mohd Kusin: Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Sharifah Nur Munirah Syed Hasan:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Verma Loretta M. Molahid:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Muhammad Hameer Soomro:** Writing – review & editing, Software, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Faradiella Mohd Kusin reports financial support was provided by Malaysia Ministry of Higher Education. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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