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Effluents and residues from industrial sites for carbon dioxide capture: a review

Francisco M. Baena-Moreno¹ · Emmanouela Leventaki¹ · Alexander Riddell¹ · Joanna Wojtasz-Mucha¹ · Diana Bernin¹

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Abstract

The adverse effects of climate change calls for the rapid transformation of manufacturing processes to decrease the emissions of carbon dioxide. In particular, a lower carbon footprint can be achieved by capturing carbon dioxide at the site of emission. Here we review the use of industrial effluents, waste and residues to capture carbon dioxide. Waste include steelmaking slag, municipal solid waste incinerator ashes, combustion fly ash, black liquor, paper mill waste, mining waste, cement waste, construction and demolition waste, waste from the organic industry, and flue gas desulfurization gypsum waste. Capture capacities range from 2 to 800 kg of carbon dioxide per ton of waste, depending on processes, waste type and conditions. Cement waste and flue gas desulfurization gypsum waste show the highest capture capacity per ton of waste.

Keywords Carbon capture and storage · Industrial effluents and residues · Capture capacity · Chemical absorption · Carbonation · Carbon mineralization

Introduction

Greenhouse gas emissions are one of the main dilemmas to be faced in the paths towards sustainable societies (Galashchev 2011; Lu et al. 2019). The reduction in carbon dioxide emissions from fossil fuels is the main concern because carbon dioxide is the most crucial greenhouse gas which is increasing due to human activity (Fawzy et al. 2020). In fact, the concentration of carbon dioxide in the atmosphere has increased from 284 in 1850 to 414 ppm in 2021 (Lindsey 2022). The straightforward reduction in these emissions via switching to renewable fuels is unlikely soon for two main reasons: (1) the main industrial technologies established are based on fossil fuels; (2) the cost of renewable energy production is in 2022 higher than with fossil fuels. An example of the last statement is the new central station electricity generating technologies. While base cost of combined cycle

power plants is approximately 1062 \$/kW, biomass and solar thermal have a base cost of around 4525 \$/kW and 7895 \$/kW, respectively (US Energy Information Administration 2022).

To address the reduction in carbon dioxide emissions, many carbon capture and storage technologies have emerged (Vega et al. 2020; Osman et al. 2021; Sharma and Dhir 2021). Examples of these technologies are physical and chemical absorption, membrane separation, and adsorption (Bui et al. 2018). A few of them have reached commercial status, such as chemical absorption with monoethanolamine (Sanna et al. 2014). Some of these commercially available monoethanolamine-based processes for carbon dioxide capture are: (1) the Kerr-McGee/AGG Lummus Crest process; (2) the Fluor Econamine FG PlusSM process; and (3) the Kansai Mitsubishi Carbon Dioxide Recovery Process (Chao et al. 2021). In 2020, nearly 26 commercial scale carbon capture plants were operating around the world, and 21 more were in early development or construction (Center for climate and energy solutions, 2022). Some authors claim that storing carbon dioxide may entail technical difficulties and that there is a lack of wells for storage (Chadwick et al. 2010; Vinca et al. 2018). Carbon leakage is one of the biggest technical barriers. So far, assuming a leakage rate of 0.1% per year, up to 25 Gt of carbon dioxide additional emissions

✉ Francisco M. Baena-Moreno
francisco.baena@chalmers.se

Diana Bernin
diana.bernin@chalmers.se

¹ Department of Chemistry and Chemical Engineering,
Chalmers University of Technology, 412 96 Gothenburg,
Sweden

could leak throughout the twenty-first century (Vinca et al. 2018).

To solve this problem, several carbon capture and utilization technologies have been proposed. Carbon mineralization, the production of fuels, chemicals, and algae cultivation, are particularly promising (Baena-Moreno et al. 2019a; González-Arias et al. 2022; González-Castaño et al. 2022a). Examples of recent reviews on these topics are collected in Table 1.

Although reviews on carbon dioxide capture already exist (see Table 1), there are no review papers on industrial effluents and residues available for carbon dioxide capture. The utilization of industrial effluents and residues decrease carbon dioxide emissions due to for example minimizing transportation and prevents waste to end up in landfill. Figure 1 showcases this idea.

Here we review the use of industrial effluents and residues to capture carbon dioxide, with focus on steelmaking slag,

Table 1 Recent reviews on carbon capture, storage, and utilization technologies from different perspectives. Information is available on carbon capture, storage, and utilization technologies. However,

reviews on carbon dioxide capture with the effluents and residues already available at industrial sites were not found

Goal of the review	References
To provide a deeper insight on carbon capture and storage technologies	Raza et al. (2019)
To review the state-of-the-art of carbon dioxide capture, transport, utilization and storage from a multi-scale perspective	Bui et al. (2018)
To present investigations on various technologies that can be harnessed to capture carbon dioxide, considering costs, socioeconomic aspects, and factors influencing public awareness	Wilberforce et al. (2021)
To gather the works carried out to evaluate public perception on carbon capture and storage	Tcvetkov et al. (2019)
To provide information on China's existing carbon capture, storage and utilization regulatory framework at the national and provincial level	Jiang et al. (2020)
To evaluate carbon dioxide capture via pre-combustion, post-combustion and oxyfuel combustion	Osman et al. (2021)
To assess opportunities and challenges of post-combustion capture techniques	Chao et al. (2021)
To gather a comprehensive list of carbon capture and Utilization technologies and applications, ranging from lab-scale research activities to commercially established uses of carbon dioxide	Baena-Moreno et al. (2019a)
To examine the latest developments in carbon dioxide capture, utilization, conversion, and sequestration from a multi-scale perspective	Zhang et al. (2020b)
To summarize the characteristics and performance of both liquid and solid carbon dioxide adsorbents for carbon dioxide capture and utilization	Gao et al. (2020)

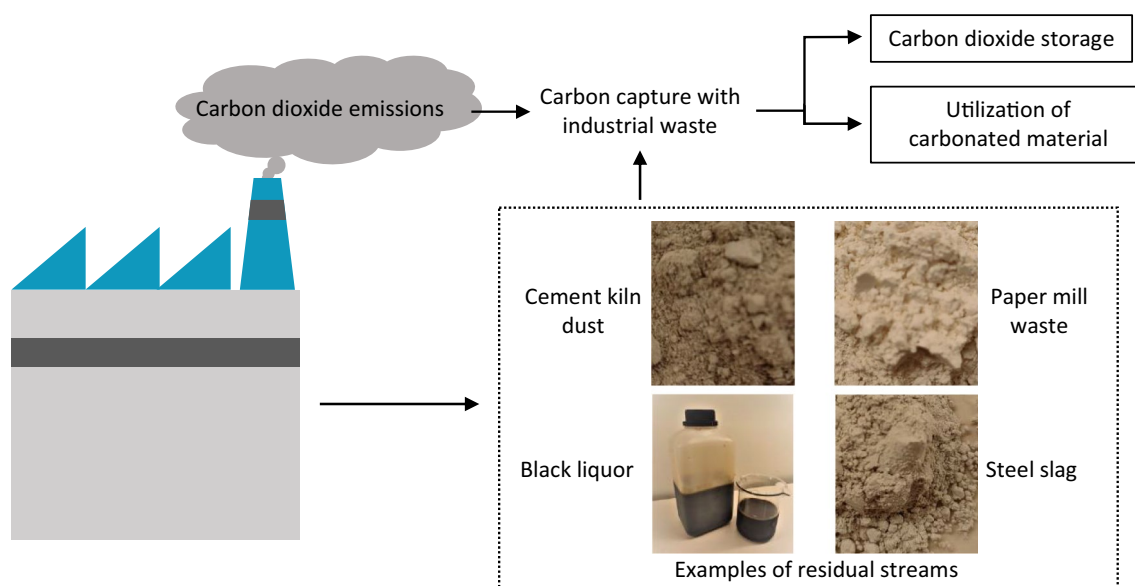


Fig. 1 Carbon capture using industrial effluents and residues. For example, black liquor, a by-product of the paper and pulp industry, could be used as an example of how an alkaline waste stream can

capture the carbon dioxide that is industrially emitted. This strategy would open two alternatives for the captured carbon dioxide: (1) to storage; (2) utilization of the carbonated material

municipal solid waste incinerator ashes, combustion fly ash, black liquor, paper mill waste, mining waste, cement waste, construction and demolition waste, waste from organic industry, and flue gas desulfurization gypsum waste. The use of these waste materials has the potential to increase the sustainability of carbon capture by eliminating the need to produce and transport adsorbents/absorbents. Additionally, it may be possible to recover value-added products from the reaction between carbon dioxide and the wastes. In the next sections, we review the wastes and in the last section, we compare the abundance and carbon capture capacity of these materials and comment on the feasibility of each option.

Steelmaking slag

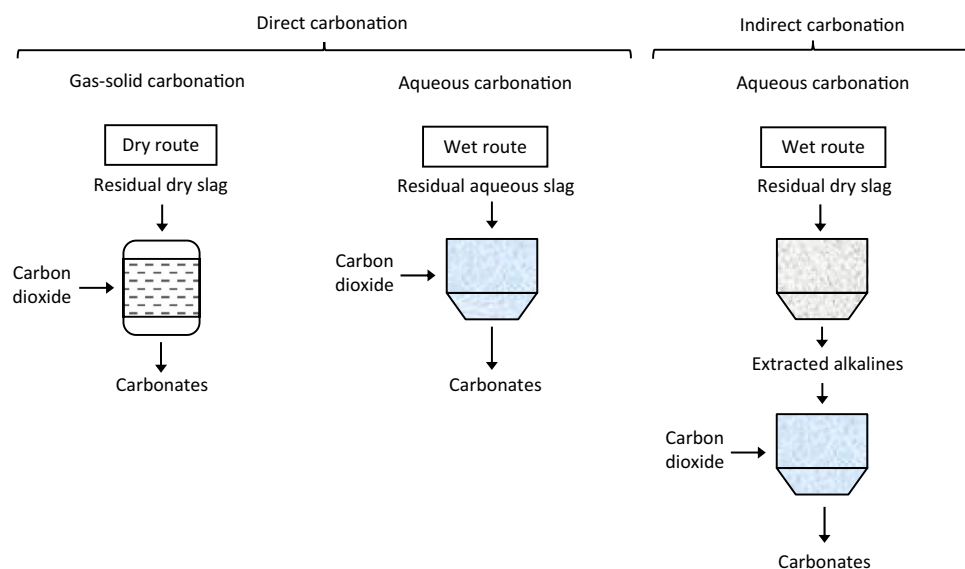
Steelmaking slag is the main by-product generated during steel refining process. It is generated during the separation of the molten steel from impurities in high temperature furnaces (Kazuhiro et al. 2013). It is estimated that between 0.13 and 0.2 ton of slag is produced for every ton of steel treated (Yu and Wang 2011), which leads to an annual worldwide production in the range of 170–250 million tons (Pacheco-Torgal et al. 2018; Joyce 2021). Many applications have been proposed for steelmaking slag, most notably to produce cement and concrete aggregate (Kazuhiro et al. 2013), and sometimes for agricultural purposes as well (Branca and Colla 2012). The high amounts of calcium oxide (20–60 w/w%) and magnesium oxide (5–10 w/w%) in steelmaking slag make it a potential candidate for carbon dioxide capture via carbonation, and different paths have been developed during the last years for this purpose (Romanov et al. 2015; Chen et al. 2021a). The main ones are schematized in Fig. 2.

The first path, the direct carbonation, is a gas–solid (dry route) or aqueous reaction (wet route) in which the slags directly react with the flue gas containing the carbon dioxide (Bodor et al. 2013). Gas–solid direct carbonation is chemically simpler than aqueous direct carbonation and occurs at temperatures around 550–700 °C (Bodor et al. 2013). However, the latter one has been more thoroughly studied because the reaction rates are considerably higher at ambient conditions and the absorption capacities are overall higher.

In the case of steelmaking slag, the absorption capacities for gas–solid direct carbonation can be approximately 10–50 g of carbon dioxide per kg of slag, while for aqueous carbonation can reach capacities of 200–300 g of carbon dioxide per kg of slag (Chen et al. 2021a). At elevated temperatures, it is expected to achieve a higher conversion of oxides to carbonates, but there is an upper limitation due to the equilibrium (Yu and Wang 2011). The composition of the flue gas is also an important factor (Yu and Wang 2011). Although one would expect to capture more carbon dioxide when the composition in the flue gas is higher, there is a threshold at which the trend changes. This trend was observed both for different temperatures and type of steel slags (Yu and Wang 2011). For example, for basic oxygen furnace slags, higher capture capacity was observed for 10 v/v% carbon dioxide composition in the flue gas than for 50 v/v% and 75 v/v%.

On the other hand, for aqueous direct carbonation, temperature has a great impact on the crystal nucleation rate, morphology of the final slag product, carbon dioxide solubility in water, and dissolution rate of the slag components (Nielsen et al. 2020). The optimal carbonation temperature for aqueous direct carbonation depends on the slag nature and varies significantly for different types of steel slags. For example, Ko et al. (2015) concluded that the optimal

Fig. 2 Carbonation routes for steelmaking slag. Direct carbonation routes consist of direct carbon dioxide reaction with either dry slags (dry route) or aqueous slag (wet route). Indirect carbonation includes an extraction stage of alkaline compounds from residual dry slags before carbonation reaction. Modified after Chen et al. (2021a)



temperature for carbonation of their slags was around 200 °C, whereas Tu et al. (2015) obtained 60 °C as the optimal temperature (Ko et al. 2015; Tu et al. 2015).

The second path represented in Fig. 2, indirect carbonation, is a two-step process that consists of alkaline metal extraction (mainly calcium and magnesium) from the slags and carbonating them. Absorption capacities of up to 250 g of carbon dioxide per kg of slag can be obtained. The main advantage of this path compared to direct carbonation is the greater purity (and subsequently its greater economic value) of the final product (Chen et al. 2021a). Nonetheless, the need of a solvent to extract the metal adds both technical and economical complexity to the process. The solvents typically used are hydrochloric acid, nitric acid, acetic acid, or ammonium salt, among others, although strong acids are preferred due to the higher leaching capacity of the metals (Wang et al. 2021). It has been evidenced that low pH values benefit metal extraction, but this process condition requires spending extra resources to get the high pH values needed for carbonation (Kodama et al. 2008).

Reaction times highly depend on the composition of the steel slag, but generally 90% of the calcium and magnesium is extracted after 20% of the reaction time needed to reach equilibrium (Bao et al. 2010; Chen et al. 2021a). The reaction temperature is a highly discussed parameter. There are authors who have claimed that the temperature does not play a key role in the reaction kinetics (Eloneva et al. 2011). Others concluded that increasing the extraction temperature from 40 to 80 °C could enhance metal extraction around 75–80% (Bao et al. 2010). Concerning particle size, there is an agreement in the literature that a lower particle size of slag favors metal extraction (Teir et al. 2007; Said et al. 2013). Finally, the liquid to solid ratio is also an important parameter to optimize. While increasing the ratio leads to higher metal extraction, the concentration of alkali metals in these mixtures is lower, leading to a lower carbonation efficiency.

As showcased here, the carbonation of steelmaking slag has been widely studied and the main factors that affect the process are known and thoroughly evaluated. Therefore, industrial application of this technology may happen in the coming decade, which could be a new sustainable path for the utilization of steel slags in the capture of carbon dioxide.

Municipal solid waste incinerator ashes

Municipal solid waste incineration has excellent properties concerning waste volume reduction and energy recovery (Clavier et al. 2020). Nonetheless, it also entails the production of municipal solid waste incineration ashes, which is a hazardous waste and hence it requires specific treatments before final disposal (Zhang et al. 2021). Two main

fractions can be distinguished within municipal solid waste incinerator ashes: (1) bottom ash, which is around 20–30 w/w% of the original waste; (2) and fly ashes, usually characterized by a higher calcium content and lower silica content compared to bottom ash (Romanov et al. 2015). The latter can be divided into fly ashes and air pollution control residue depending on the country. Many treatment strategies are available for these ashes, depending on the waste composition, type of combustion unit and air pollution control devices (Zhang et al. 2021). Nonetheless, their high calcium, sodium, and potassium content (see Table 2) make them suitable for carbon capture via carbonation.

Similarly, to the steelmaking slag case, different carbonation routes are possible, with similar effects. Previous authors have proposed different strategies for carbonation of municipal solid waste incinerator ashes. Concerning bottom ashes, Fernández-Bertos et al. (2004) presented a systematic evaluation of aqueous direct carbonation through the variation of reaction time, particle size, and liquid to solid ratio. They obtained an initial rise in carbon dioxide capture, higher capture rate for lower particle sizes and an optimal for liquid to solid ratio; results which agree with the trends previously explained for steel slag (Fernández Bertos et al. 2004). Rendek et al. (2006) proposed carbonation of bottom ash with the final combined aim to pacify the ashes and obtain an amount of carbon dioxide that could be captured. The carbon dioxide volume captured was in the range of 12.5–24 L/kg dry matter, being higher for sieved samples (Rendek et al. 2006).

Accelerated aqueous carbonation was proposed by Baciocchi et al. (2010) to capture carbon dioxide with bottom ash from refuse-derived fuel incineration (Baciocchi et al. 2010). These authors also divided the ashes in different fractions by particle size, obtaining 4 w/w% carbon dioxide uptake for

Table 2 Approximate composition ranges for major constituents of bottom ashes, fly ashes and air pollution control residues. As can be seen the composition in calcium is very high. This fact makes them suitable for carbon dioxide capture. Furthermore, the sodium and potassium composition may enhance the carbon dioxide capture capacity of the ashes. Modified after Belevi et al. (1992), Šyc et al. (2020), Zhang et al. (2021)

Chemical (w/w%)	Bottom ashes	Fly ashes	Air pollution control residues
Calcium	10–17	12–24	22–40
Silica	4–30	4–9	1–4
Sodium	23–42	6–10	0–4
Potassium	6–15	1–8	0–6
Iron	3–15	1–3	0–2
Alumina	5–7	2–8	0–4
Magnesium	14–16	1–4	0–3
Chlorides	1–4	3–12	1–21

coarse fractions and 14 w/w% for the finest ones. This fact reveals a high influence of the overall particle size of the ash (Baclocchi et al. 2010).

The type of reactor (fixed bed and rotating drum) for carbonation of bottom ashes was also studied for carbon dioxide capture (Lombardi et al. 2016). The aim was to improve the contact and mixing between bottom ashes and landfill gas. They concluded that the rotating drum offered an improved capture over the fixed bed reactor type, in particular when it was operated at low filling ratio and slow rotating speed values. At most favorable conditions, the capture capacity was improved from 21 to 23 g/kg of bottom ash in fixed bed to 35–37 g/kg of bottom ash in rotating drum reactor. On the contrary, Brück et al. (2018) observed in a similar study that, within the range they tested (7–45% of total capacity), the filling ratio was not a limiting factor. It seems that this parameter could be further optimized. These authors also observed that the carbonation increases as the concentration of carbon dioxide in the flue gas increases (Brück et al. 2018).

Other works have explored the carbonation of fly ashes and air pollution control residues coming from incineration. A successful study for direct aqueous carbonation of incinerator air pollution control residues was carried out (Baclocchi et al. 2009). Under 100 v/v% carbon dioxide flue gas, these authors obtained a capture capacity of approximately 250 g/kg of air pollution control residues. Similar studies were carried out for air pollution control residues by the same authors but following the direct gas–solid carbonation route (Baclocchi et al. 2006; Prigiobbe et al. 2009). At 400 °C, around 120 g/kg of air pollution control residues were captured. The differences found in these studies remark the importance of the carbonation route selected.

Another work proposed the use of air pollution control residues as sorbents in the calcium looping process (Dal Pozzo et al. 2018). This process implies multiple carbonation–calcination cycles. The sorbents get carbonated with the carbon dioxide during the carbonation stage, and then calcined during the calcination stage, releasing the carbon dioxide absorbed. The authors reported that air pollution control residues presented sorption capacities slightly lower than those of limestone, which is the benchmark raw material used for calcium looping (Dal Pozzo et al. 2018).

Examples of investigations for evaluating the carbon dioxide capture capacity in fly ash carbonation are described next. Jiang et al. (2009) evaluated the importance of hydrous reaction conditions, obtaining approximately 30% improvement in capture capacity when adding 20% water to the reaction (to a pure carbon dioxide gas) (Jiang et al. 2009). Six fly ash samples from different incinerators were physiochemically characterized, with the intent of using them for carbon dioxide capture in the calcium looping process described above, but for thermochemical energy storage (Setoodeh

et al. 2019a). Operational characteristics (i.e., charging, discharging, or cycling stability) were evaluated. For a representative fly ash, authors obtained a capture capacity of 27 kg/ton fly ash in a simultaneous thermal analysis in direct gas carbonation mode (Setoodeh et al. 2019a).

Bui-Viet et al. (2020) explores the use of incineration fly ash for capturing carbon dioxide and then using the final product as supplementary cementitious material, a combined approach for the transition to circular and green construction materials (Bui Viet et al. 2020). Unfortunately, the carbonation capacity of the ashes was very poor (3.1 mg/g of fly ash). A high-gravity rotating packed bed was used for carbon dioxide sequestration via incineration fly ash carbonation. The effects of the liquid-to-solid ratio and high gravity factor were evaluated. They obtained a carbon dioxide capture capacity of around 260 g/kg of incineration fly ash (Chen et al. 2021b).

All in all, municipal solid waste incinerator ashes can be used for carbon dioxide capture, as shown in previous studies. The gas–liquid carbonation route seems to be particularly appealing for air pollution control residues, obtaining capture capacities of around 250 g/kg of air pollution control residues.

Combustion fly ash

Combustion fly ash is a primary by-product obtained from solid fuel combustion (Ukwattage et al. 2013a). This type of fly ash differs greatly in composition from the incineration fly ash due to the different manufacturing processes. Even though the calcium oxide composition is similar for both types of ashes, substantial differences can be found in the rest of the components, which could affect the carbonation performance. For example, the alumina, silica and iron oxide content are usually greater in combustion fly ash than in incineration fly ash, while the latter is usually richer in potassium and sodium oxides (Soong et al. 2006; Setoodeh et al. 2019b). A pioneer work in which combustion fly ash was proposed for carbon dioxide sequestration was presented by Soong et al. (2006). These authors used the fly ash to increase the pH of a brine, both the fly ash and the brine were obtained from oil and gas production (Soong et al. 2006). Authors concluded that the calcium from both the ashes and the brine contributed to produce calcium carbonate via carbonation at mild temperatures (approximately 60 °C).

Uliasz-Bocheńczyk et al. (2009) estimated that the capture capacity of this type of ash is approximately 7.2 g/100 g of ash, a value which has the same range as the ones obtained by other authors (0.766–2.7 g/100 g of ash) (Uliasz-Bocheńczyk et al. 2009; Montes-Hernandez et al. 2009; Ukwattage et al. 2013b, 2015; Ji et al. 2019).

These results are lower than the results obtained when using incineration fly ashes, which could be due to the greater alumina and silica composition. Greater carbon dioxide capture capacity (21 g/100 g of ash) was obtained using the combustion petroleum coke fly ash likely due to a lower alumina and silica content. Unfortunately, this possibility could not be evaluated because the composition of the ashes was not available (González et al. 2014).

Other works have proposed the use of fly ash as a raw material to prepare other compounds for carbon dioxide capture and utilization. For instance, sodium/lithium-silicate sorbents were prepared by mixing sodium/lithium carbonates with fly ash (Sanna et al. 2015). Authors obtained very promising results concerning the absorption/desorption rates after 10 cycles at 700 °C. Furthermore, the capture capacity and stability over time was comparable to the one obtained with commercial sorbents (i.e., calcium oxide and hydrotalcites). In another work, zeolites were synthesized from combustion fly ash from a coal power plant, revealing a high adsorption capacity at moderate temperatures (83% of the commercial benchmark at 50 °C) (Morales-Ospino et al. 2020).

Recently, Dong et al. (2020) proposed the use of coal combustion fly ash as nickel-rhenium bimetallic catalyst support for carbon dioxide utilization via methanation reaction (Dong et al. 2020). Methanation consists of transforming carbon dioxide and hydrogen into methane in the presence of a catalyst. This reaction has raised a lot of interest during the last decade as the final methane product is a useful substitute to traditional fossil natural gas (González-Castaño et al. 2022b, c). Therefore, using fly ash as a cheap catalyst support for methanation gives an extra added value of circularity to the utilization of waste materials for carbon dioxide capture and utilization. The overall process of this idea is presented in Fig. 3. The authors that proposed this idea obtained a carbon dioxide conversion of 99.55%, with a methane selectivity of 70.27%, at 400 °C and 1 atm.

From the data gathered above, one may conclude that combustion fly ash may be a worse candidate than other

types of ashes for carbon dioxide capture. Nonetheless, these types of ashes could still participate indirectly in carbon dioxide capture and utilization processes (as the one shown in Fig. 3).

Black liquor

One of the main wastes of the pulp and paper industry is black liquor; a high pH, aqueous solution composed of lignin, hemicellulose, carboxylic acids, and inorganic chemicals (Pratima 2018; Reyes et al. 2020). This waste comes from the cooking process. Among the inorganic chemicals, sodium species are the most predominant ones, as shown in Table 3. This predominance is due to sodium hydroxide being typically used as cooking agent (Reyes et al. 2020). The high concentration of sodium species at high pH makes black liquor suitable for carbon dioxide capture via aqueous carbonation.

Black liquor has been traditionally carbonated to decrease pH, allowing to recover carboxylic acids and lignin (Kumar and Alén 2015; Kumar et al. 2016). Therefore, the parameters evaluating the performance of carbon dioxide capture were not reported. Indeed, there are a few works describing the conditions in which black liquor could be successfully

Table 3 Black liquor composition ranges (main components). The data gathered reveal the high composition in sodium. This, along with other inorganic chemical compounds found in black liquor, make it potentially suitable for carbon dioxide capture. Modified after Demirbaş (2002), Cardoso et al. (2009), Carlsson et al. (2010)

Parameter	Composition (% mass per dry solids)
Carbon	29–40
Nitrogen	0–1
Hydrogen	3–5
Potassium	1–4
Sodium	8–22
Silica	0–4
Sulphur	0–6
Chlorides	0–5

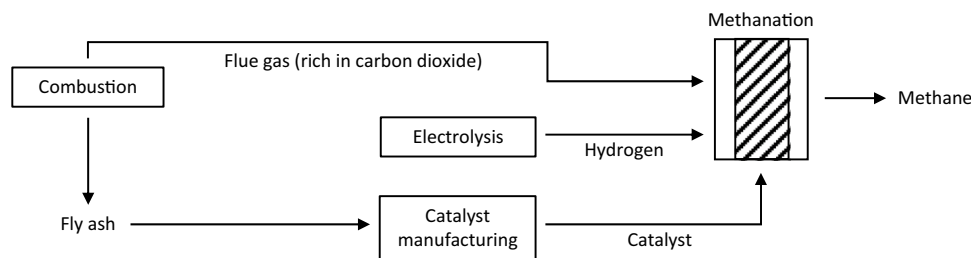


Fig. 3 Utilization of combustion fly ashes to produce catalysts for carbon dioxide methanation. The fly ash obtained in the combustion stage will serve as catalyst support for methanation reaction. The flue gas emitted in the combustion stage could be the carbon dioxide

source for methanation reaction. A source of hydrogen will be also needed, for example through electrolysis of water. Fly ash could be a cheap catalyst support, which would not only give the process circular aspects, but could also make it economically appealing

carbonated (Kumar and Alén 2015; Mandavgane and Subramanian 2016). For example, Kumar and Alén (2015) decreased the pH of black liquor to approximately 8.5 by treatment with pure carbon dioxide at 1.5 bars and 80 °C for 40 min (Kumar and Alén 2015).

The scarce literature on the topic leaves further room for investigation of black liquor carbonation with the aim of capturing carbon dioxide. Carbonation of black liquor and recovery of other products could be combined for an enhanced circular economy, as shown in Fig. 4. The first step would be carbonation of black liquor to both capture carbon dioxide and decrease the pH of the black liquor for later recovery of by-products. An extra by-product obtained in this first step would be precipitated lignin, which could need extra post-treatment for removing impurities or enhancing the final product quality. Once the black liquor is carbonated, one could opt either for direct product recovery, for example via electrodialysis to obtain sodium hydroxide and carboxylic acids, or further acidification to precipitate more lignin. The evaluation of this process has been partially studied, but as aforementioned, further research studies are needed for the carbonation side with a carbon dioxide capture perspective.

As the main conclusion of this section, we can highlight that further studies on black liquor carbonation are needed to evaluate the capture capacity of this waste. Furthermore, strategies to recover chemicals from the carbonated black liquor need to be developed.

Paper mill waste

Carbon dioxide capture using wastes from paper mills is also possible. However, as in the previous case, only a few works have been reported up to date. Alkaline paper mill waste contains a high percentage of calcium hydroxide (Lim et al.

2010). Therefore, this waste can be used for carbonation, as discussed in previous sections.

Pérez-López et al. (2008) used an alkaline paper mill waste called calcium mud, which is the waste obtained after the calcination/conversion of calcium carbonate to lime to alkalize black liquor (Pérez-López et al. 2008). The approximate composition of this waste, without including minor compounds, was 55 w/w% calcium hydroxide, 33 w/w% calcium carbonate, and 12 w/w% hydroxyapatite. The reaction conditions were varied between 30–60 °C and 10–40 bar, and the experiments were carried out for 2 h. The authors found that 218 kg of carbon dioxide could be transformed into stable calcium carbonate per every ton of paper mill waste. The type of calcium carbonate obtained by the authors was calcite, which has many industrial applications (Baena-Moreno et al. 2019b). The same authors later proposed a very successful application for the carbonate produced as acidity neutralizing agents for treatment of acid mine (Pérez-López et al. 2010). According to the results obtained by these authors, there is enough annual amount of alkaline paper mill waste to treat between 40 and 114 L per second of acid mine drainage.

Another interesting study was recently presented by Spínola et al. (2021). In this work, the grits, another alkaline paper industrial waste rich in calcium, sodium, and magnesium, was used for carbon dioxide capture via indirect carbonation (Spínola et al. 2021). Typical calcium, sodium and magnesium composition in grit can be seen in Table 4. Four solvents were used for evaluating the extraction of valuable compounds from the grit: nitric acid, acetic acid, sodium hydroxide, and ammonium chloride. The best efficiencies were for nitric acid and acetic acid (79.4% and 73.2%, respectively). Carbonation tests were carried out with acetic acid to avoid potential problems that nitric acid may cause due to its corrosive nature. Optimal carbonation efficiencies of 74% of the theoretical maximum at 30 °C and 30 bar were obtained. This result corresponds to a carbon dioxide

Fig. 4 Black liquor carbonation, a process which fits with the concept of a circular economy. The process idea includes carbonation of black liquor followed by separation of lignin. The carbonated black liquor could then be sent to electrodialysis or to further acidification for chemicals recovery. Examples of chemicals that could be recovered are sulfuric acid and sodium hydroxide

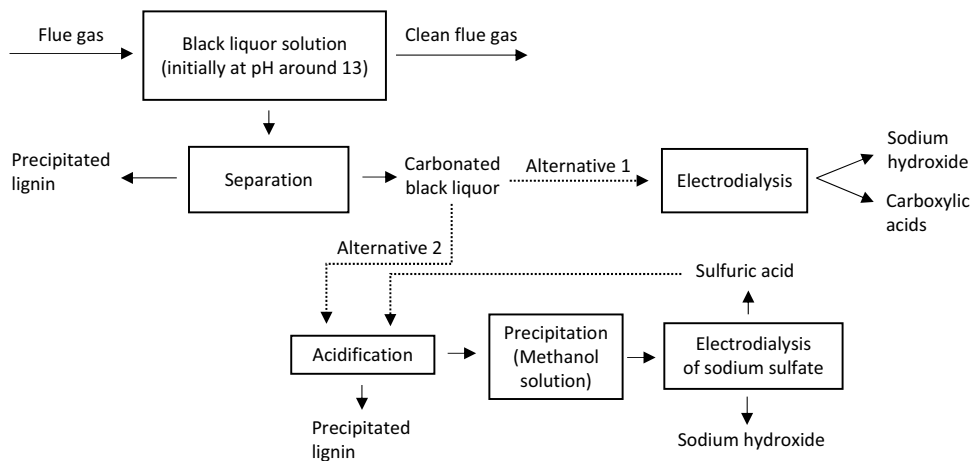


Table 4 Approximate concentration of calcium, sodium, and magnesium in grits. The concentration of these inorganic species is high enough to consider grits as potential waste for carbon dioxide capture. In fact, the high composition in calcium, make the grits very suitable for carbonation. Modified after Martins et al. (2007), Cabral et al. (2008), Watkins et al. (2010), Farage et al. (2020), Spínola et al. (2021)

Parameter	Composition (g/kg)
Calcium	330–420
Sodium	10–65
Magnesium	3–9
Iron	2–10

sequestration capacity of approximately 460 kg per ton of grits (Spínola et al. 2021).

The gas–solid alternative for carbon dioxide capture via carbonation has been also proposed for lime mud, a solid waste coming from the causticization of paper during the manufacturing process (Sun et al. 2013). Authors obtained a lower performance of carbonation for lime mud compared to the benchmark limestone (0.4 vs. 0.8 over 1 carbonation efficiency for first cycle, respectively) due to the high chlorine content leading to more sintering. To improve the overall efficiency, authors proposed a pre-wash stage to decrease the chlorine content. Although the results showed improvement over the lime mud without treatment, they were still far from the benchmark. Despite the lower efficiency, this alternative can be promising if high quantities of lime mud are available.

Due to the very high content on calcium, paper mill waste is an interesting candidate for carbon dioxide capture. In fact, the use of both black liquor (with high content on sodium) and paper mill waste (high content on calcium) may cut-off considerably carbon dioxide emissions in paper and pulp industry and lead to negative emissions.

Mining waste

The first studies proposing the use of mining waste for carbon dioxide capture via carbonation are only a decade old, so much further research is still possible. Examples of these pioneer studies are described below. Ultramafic mining waste (a mine waste rich in magnesium and iron) was proposed for mineral carbonation (Pronost et al. 2011). They explored both the maximum amount of carbon dioxide that could be captured and the reaction rate at different experimental conditions. The parameters varied were humidity, temperature, and the concentration of carbon dioxide. They found that 8 w/w% of the sample was carbonated for the most reactive samples. They also found that nesquehonite and dypingite were formed on the carbonated phase, which

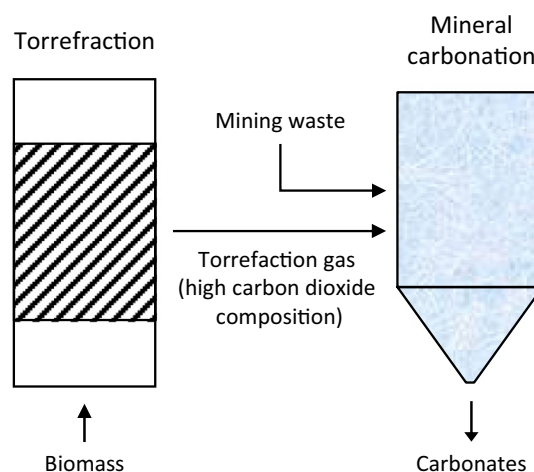


Fig. 5 Combined biomass torrefaction and mineral carbonation with mining waste. The gas coming from torrefaction of biomass has a high composition on carbon dioxide. Mining waste could be carbonated using the carbon dioxide of this torrefaction gas. This process would be considered as negative emissions technology since biomass is carbon dioxide neutral. Modified from Sarvaramini et al. (2014)

could be potentially used as commercial added-value materials (Pronost et al. 2011).

Chrysotile, a rich magnesium mining waste, was also proposed as a carbon dioxide capture material (Assima et al. 2012). They found that carbonation was very sensitive to water content. The carbon dioxide uptake was only 0.02 w/w% of the stoichiometrically calculated value for dry samples and was 20 times better with small water additions. Nonetheless, the maximum capture capacity obtained was 22 mg of carbon dioxide per gram of waste. Therefore, around 90 w/w% of the magnesium remained uncarbonated due to surface obstructions.

Serpentine mining residues (containing about 40 w/w% magnesium oxide) were tested for carbon dioxide capture following the direct gas–solid carbonation route (Veetil et al. 2014). Authors focused on calculating the carbon dioxide removal efficiency rather than in the adsorption capacity. They found optimal conditions at 258 °C under 5.6 bar, for 310 min, obtaining a removal efficiency of 37%.

A novel study was presented by Sarvaramini et al. (2014) in which a combined biomass torrefaction and carbon dioxide capture with mining residues process was proposed (Sarvaramini et al. 2014). The mining wastes were two different magnesium-rich ultramafic mining wastes. The process for this innovative circular idea is shown in Fig. 5. Authors found that about 22–62% of carbon dioxide can be captured with these wastes. The most important differences between the wastes were attributed to their different contents in brucite, a form of magnesium hydroxide.

Another finding of these authors was the high temperature effect on the carbonation rate. Increasing the reaction temperature led to improved carbon dioxide capture, but more frequent watering of mining waste would be needed. Decreasing the carbon dioxide content in torrefaction gases implies a higher concentration of non-condensable gases, hence increasing chances for burning and heat integration (Sarvaramini et al. 2014).

Apart from the previously described works, other studies on isolated wastes have been carried out. For example, passive mineral carbonation of rich magnesium waste by atmospheric carbon dioxide was studied (Beaudoin et al. 2017). As in the works previously described, authors found that watering is of crucial importance to optimize the carbonation reaction. The feasibility of iron-silicate mining waste carbonation was also explored (Reynes et al. 2021). Authors proposed the route of iron complexation using 2,2'-bipyridine. The overall process consisted of leaching, iron complexation, and aqueous mineral carbonation. A carbon dioxide uptake of approximately 57 w/w% was obtained. Considering this result, authors estimated that about 130 kg of carbon dioxide per ton of residue could be captured (Reynes et al. 2021).

Finally, techno-economic evaluation and life cycle assessments for using mining waste for carbon dioxide capture have been performed. From the economic side, a process model for using serpentine mining waste for carbon capture was developed. The model was used to estimate that the global process cost would be approximately \$144 per ton of carbon dioxide and revenue would be about \$644 per ton of carbon dioxide. The importance of this work is crucial since it revealed that using mining waste for carbon dioxide capture may be profitable (Pasquier et al. 2016). Furthermore, from a life cycle assessment perspective, Bodénan et al. (2014) evidenced that mining waste carbonation for carbon dioxide capture can be environmentally viable if operating conditions are optimized (Bodénan et al. 2014).

Even though some research works have been carried out for carbonation of mining waste, there are still many unknowns regarding evaluation of capture capacities and the performance of other mining-type waste. Therefore, extending the research available is a must to advance in the utilization of mining waste to capture carbon dioxide.

Cement waste

The cement industry is one of the main contributors to the anthropogenic release of carbon dioxide, as it accounts for 5–7% of the overall emissions (Benhelal et al. 2013). The high levels of emissions are due to two main reasons: (1) producing of cement is an energy-intensive; (2) concrete is the building block of all modern constructions (Gagg 2014;

Skocek et al. 2020). Cement makes up 10–15 w/w% of concrete (Gagg 2014). It is an inorganic binder that is wetted to form a paste which is then mixed with coarse and fine aggregates as well as other additives, giving the material the desired mechanical properties (Melander et al. 2003). Cement contains calcium oxide (63–67 w/w%), silica, alumina and other metal oxides in smaller concentrations (Telford 1999). Calcium oxide, also known as lime, is the major compound and it is derived from the calcination of limestone (at approximately 900 °C) (Gagg 2014).



The introduction of carbon dioxide capture in the life cycle of cement has been under intense examination for two reasons. Firstly, its high greenhouse gases emission footprint requires a circular process. Secondly, its high content of calcium and other metal oxides makes it a very attractive raw material for carbonation with carbon dioxide, the reverse reaction of Eq. (1) (Haselbach 2009). A by-product from the production of cement clinker is cement kiln dust, a fine-grained solid collected in the exhaust of the kiln (Miller and Azad 2000). A large part of it is recycled into the process, but the rest is disposed in landfills. The composition of cement kiln dust varies depending on the raw materials and conditions in the kiln. Typical compositions of this waste are shown in Table 5.

The sequestration of carbon dioxide in cement kiln dust was tested at ambient pressure and temperature (Huntzinger et al. 2009a, b). The results showed that 60–70% carbonation of the cement kiln dust happens readily, while it is rather difficult to achieve values higher than 80%. Another work conducted by Youn et al. (2019) investigated a three-step sequestration of carbon dioxide. In this process, potassium and calcium chloride were extracted from cement kiln dust

Table 5 Typical range of concentrations of main compounds in cement kiln dust. The data collected reveal the high composition in calcium oxide. This calcium oxide can be carbonated, hence forming calcium carbonate. The calcium carbonate product could be reused in cement manufacturing. Modified after Siddique (2008), Siddique (2014)

Compound	Composition (w/w%)
Calcium oxide	40.50–63.76
Silicon dioxide	2.16–17.10
Aluminum oxide	1.09–4.24
Magnesium oxide	0.68–1.93
Sodium oxide	0.33–3.84
Potassium oxide	0.11–4.66
Iron oxide	0.54–2.86
Sulfur trioxide	0.05–6.50
Loss of ignition	5.38–42.39

and subsequently reacted with carbon dioxide (Youn et al. 2019). This research focused on the extraction of metal chlorides, which are present in cement kiln dust when chlorine-rich waste plastics are used as fuel for the kiln.

Other papers have also been published on the extraction of metals from the cement waste and combination with ammonium-based compounds for carbon capture (Pedraza et al. 2021). A techno-economic assessment proposed the mineral carbonation of cement kiln dust by combining the waste with flue gas on site to produce mineral carbonates. The final product can then be utilized in the cement industry as non-reactive fillers (Pedraza et al. 2021).

Generally, the high content of calcium oxide makes cement waste attractive to capture carbon dioxide. Nonetheless, due to the high volume of emissions of carbon dioxide in the production of cement, this waste will not considerably reduce the carbon dioxide emitted. However, carbonation of these waste may be a good strategy to avoid landfill disposal and re-using the carbonates formed in the same industry.

Construction and demolition waste

Wastes originating from construction and demolition contain a lot of calcium hydroxide and calcium silicate hydrate, which can be used to sequester carbon dioxide (Engelsen et al. 2005; Kaliyavaradhan and Ling 2017). Construction and demolition wastes contain a mixture of various materials, like crushed concrete, asphalt, glass, mixed demolition debris and others (Silva et al. 2014). Since this waste is produced in very high quantities, research is focused on finding uses for it in the construction industry. The wastes that are reused for production of concrete are called recycled aggregates. Their reincorporation as a raw material is not common, because their mechanical properties are poor. Moreover, replacement of concrete at high concentrations will downgrade the final product.

Therefore, researchers have proposed the carbonation of recycled aggregates to capture carbon dioxide. This process lowers the carbon footprint of concrete and at the same time upgrades the characteristics of the waste. The enriched aggregates can be reused in concrete production and enhance the overall quality of the product (Kaliyavaradhan and Ling 2017; Zhang et al. 2020a; Gomes et al. 2021). The durability and mechanical properties of carbonated recycled aggregates showcase superior properties compared to non-carbonated ones, making them suitable for reuse in concrete (Xuan et al. 2016, 2017).

Carbonation occurs naturally throughout the lifetime of concrete through a process called weathering carbonation (Kaliyavaradhan and Ling 2017). Carbon dioxide encounters the surface of the concrete. The rest of the material, that is not exposed to the atmosphere is still highly alkaline and

can be used for active carbonation. Most of the literature has investigated the adsorption of carbon dioxide in construction and demolition waste with a setup like the one shown in Fig. 6 (Engelsen et al. 2005; Kou et al. 2014; Zhan et al. 2014).

The reaction takes place inside a carbonation chamber, that is first vacuumed to a very low pressure and then 100 v/v% carbon dioxide is introduced. Silica gel is also present to absorb the released water, which might hinder the reaction. Xuan et al. (2016) carried out large scale experiments with this setup at various pressures for 24 h. They reported that in average 7.9 kg of carbon dioxide was captured per ton of recycled concrete aggregates (Xuan et al. 2016). The highest absorption was 8.1 kg per ton for the aggregates of the finest particle size under 5 bars of pressure. Cai et al. (2018) investigated the sequestration of carbon dioxide in construction and demolition waste in a fluidized bed, where carbonation/calcination cycles were conducted under high temperature (Cai et al. 2018). The percentage of carbonation was highly dependent on the hydration treatment of the samples prior to the reaction cycles.

The carbonation performance of construction and demolition waste is largely dependent on the particle size and level of humidity. Particle size and porosity are the factors which determine the contact area between the gas and solid phases. Hence, the finer and more porous a material is the more carbon dioxide is absorbed, as has been verified in the literature (Engelsen et al. 2005; Kaliyavaradhan and Ling 2017; Gomes et al. 2021). Humidity has been found to be favorable at around 50–70 v/v%, as a higher-level results in water entering the pores and dissolving the metal ions so

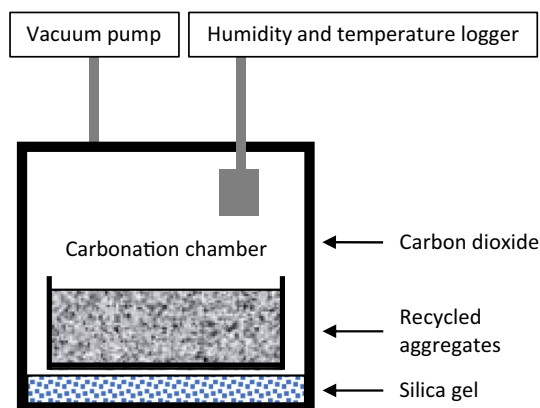


Fig. 6 Standardized experimental setup for evaluating the capture capacity for the carbonation reaction of construction and demolition waste. Most researchers have followed this setup with small alterations. The way of flowing carbon dioxide, duration of reaction, and waste composition vary in each work. Nevertheless, the process usually takes place in a closed chamber with strict control on the humidity and pressure. Modified after Kaliyavaradhan and Ling (2017)

that the reaction is limited by diffusion. A relative humidity lower than 50 v/v% does not provide sufficient moisture for the reaction to take place (Cai et al. 2018; Elsalamawy et al. 2019).

Another noteworthy publication by Moghtaderi et al. (2012) proposed the use of construction and demolition waste in the gasification process as a sorbent for carbon dioxide (Moghtaderi et al. 2012). The emission of carbon dioxide is one of the few downsides of the gasification technology. In this study, construction and demolition waste was introduced in the gasification chamber to sequester the produced carbon dioxide and in a next step it was again released in a gas form, to be stored permanently underground.

In contrast with previous analyzed wastes, humidity seems to be a limiting factor for the carbonation of construction and demolition waste. This fact entails an extra-added cost to control the humidity levels which should be considered when evaluating carbonation of construction and demolition waste. Nevertheless, the carbonated aggregates enhanced mechanical properties in concrete.

Waste from the organic industry

Organic solvents find application in many industries to produce a wide range of chemicals, from paints and coatings to pharmaceuticals. The most common solvents used are alcohols, ketones, esters, hydrocarbons, and others (Fortune Business Insights 2022; Transparency market research 2022). After their use, these chemicals are either recovered for reuse, or incinerated (Jimenez-Gonzalez 2019). Furthermore, the production processes of these chemicals produce many different organic based wastes.

The most used solvents for the absorption of carbon dioxide are the alkanol-amine groups, monoethanolamine and diethanolamine. However, their two main disadvantages, namely corrosivity and energy-consuming recovery, incite researchers to search for alternative candidates for absorption. Therefore, solvent organic waste coming from organic industries seems like an attractive option to explore. Although, up to date, there are no papers on the utilization of these organic wastes, we believe that this waste needs to be further exploited by the scientific community. Therefore, the works below using organic products for carbon dioxide capture, will encourage researchers in opening new research avenues in this field.

Extensive studies have been conducted on the use of methanol and ethanol, which are among the most used industrial solvents to capture carbon dioxide by coupling them with potassium or sodium hydroxides to induce chemical absorption (Han and Wee 2016, 2017; Mun et al. 2018; Pak et al. 2022). In one of their studies, they proposed the use of aqueous solutions of ethanol (60–100 w/w%) with 3 g

of potassium hydroxide to produce potassium carbonate, bicarbonate and ethyl carbonate, in a series of bubble columns at ambient conditions (Pak et al. 2022). The highest absorption of carbon dioxide and production of potassium ethyl bicarbonate was observed for the solution of 90 w/w% ethanol. Similarly, solutions of aqueous ethanol (50.5–97 w/w%) were tested with sodium hydroxide, this time in a single column, for the production and precipitation of sodium bicarbonate (Mun et al. 2018). It was found that the maximum formation of sodium bicarbonate was for 80 w/w% ethanol, while for higher concentrations of ethanol, sodium ethyl carbonate was favored and precipitated.

In another study, sodium hydroxide was dissolved in ethanol for carbon dioxide capture and subsequent production of unstable sodium ethyl carbonate. This product could then be dissolved in water for the recovery of ethanol and formation of sodium bicarbonate (Han and Wee 2016). Lastly, the same group tested the use of sodium hydroxide dissolved in various concentrations in pure methanol for a combination of physical and chemical absorption (Han and Wee 2017). Sodium methyl carbonate and sodium carbonate were synthesized, and methanol was regenerated by evaporation to be reused in the process. It should be noted that in all these investigations, the absorption of carbon dioxide and precipitation of solid carbonates were observed within minutes.

Other works have investigated the phenomena taking place in systems of supersaturated calcium carbonate with monoethylene glycol, a mixture that is often used as a hydrate inhibitor in oil production (Serpa et al. 2017; Natsi et al. 2019). Natsi et al. (2019) observed that in the presence of monoethylene glycol, calcium carbonate would form aragonite and vaterite structures which would otherwise be unstable at normal environmental conditions (Natsi et al. 2019). Chowdhury et al. (2020) conducted a screening of 18 alcohol solvents to be used with amine absorbents that yielded higher absorption capacities and resulted in easier recovery of the captured carbon dioxide (Chowdhury et al. 2020). The mixture of 2-(ethylamino)ethanol with triethylene glycol (80:20 w/w%) had the best performance in terms of capture capacity. The recovery of carbon dioxide was greater than in the case of 2-aminoethanol. In another case, 2-[(1,1-dimethylethyl)amino]ethanol and 1-[(1,1-dimethylethyl)amino]-2-propanol were dissolved in ethylene glycol and carbon dioxide was captured due to the formation of reversible zwitterionic carbonates, from which the gas is easily recovered (Im et al. 2011).

In the literature above, the formed products were on purpose unstable to regenerate the gas for utilization or storage. However, more stable organic carbonates can be useful for a range of applications (Sakakura and Kohno 2009). For example, they can be used as building blocks in the synthesis of plastics, as electrolyte solvents for lithium-ion batteries and they are also quite good organic solvents. The

production of these types of organic carbonates takes place under more vigorous conditions in the presence of a catalyst and usually under high pressure.

Overall, even though some studies have been performed to carbonate organic compounds, further research is needed to utilize organic solvent waste. Furthermore, combination with other inorganic compounds (such as calcium and magnesium species) may enhance the process performance.

Flue gas desulfurization gypsum waste

Desulfurization gypsum waste obtained from scrubbing flue gas has several advantages for carbon dioxide capture: (1) the material is cheap; (2) it is available near power plants producing large amounts of carbon dioxide; (3) it reacts relatively quickly with carbon dioxide due to the chemical instability of its composition (Wang et al. 2009). In fact, the high composition of calcium sulfate dihydrate, >95 w/w% in most of the cases (Wang et al. 2009; Song et al. 2014, 2015), makes flue gas desulfurization gypsum waste a great source of residual calcium to produce calcium carbonate by reaction with carbon dioxide (Koralegedara et al. 2019). This particular characteristic has triggered many works to focus on precipitating calcium carbonate from flue gas desulfurization gypsum waste. Song et al. (2012) explored which calcium carbonate can be formed from flue gas desulfurization gypsum waste (Song et al. 2012). They found that precipitation via direct carbonation resulted in a mixture of vaterite and calcite, while indirect carbonation (or two-step carbonation, as they named it) produced mainly calcite. A high economic value of vaterite due to its utilization in the pharmaceutical and the textile industry set off further research.

The same authors, in a later work, developed a method forming vaterite from carbonation of flue gas desulfurization gypsum waste during the induction period (Song et al. 2014). They studied the factors which potentially affect the precipitation efficiency and the quality of the calcium carbonate. Overall, they found that the formation efficiency increases linearly with the ammonia content with a maximum for the solid to liquid ratio around 5 g/L (Song et al. 2014). Later in another work, they changed the induction agent from ammonia to ethanol to obtain aragonite, which is another high added-value form of calcium carbonate (Song et al. 2015).

The same group of authors also added polyacrylic acid during the induction period to enhance the dissolution of calcium ions from the flue gas desulfurization gypsum waste (Song et al. 2016). They reported that adding 2.7 g/L of polyacrylic acid dissolved up to 60% of calcium. Conversion of waste gypsum into calcium carbonate by ultrasonic

carbonation has also been explored (Wang et al. 2020). The reported increase in efficiencies from 60 to 98% with ultrasonic amplitude and the formation of pure vaterite are promising.

Works that focused on carbonation of flue gas desulfurization gypsum waste to capture carbon dioxide, mostly studied the effect of different operational parameters such as temperature, flue gas flow rates, reaction times, and liquid to solid ratio (Lee et al. 2012a; Tan et al. 2017; Rahmani 2018, 2020). The authors reported carbon dioxide conversion efficiencies of up to 90–95% (Lee et al. 2012a; Tan et al. 2017). Increasing the reaction temperature increases the reaction rate, shortening reaction times to reach full conversion (Tan et al. 2017). Furthermore, a high liquid to solid ratio seems to favor the stability of the reaction and the quality of the final calcium carbonate. Lee et al. (2012a) showed that the use of excess ammonia (110–120%) improved both factors.

As can be seen, many works have studied the carbonation of flue gas desulfurization gypsum waste to capture carbon dioxide. Nevertheless, all these works used typical flue gas compositions with a carbon dioxide content of approximately 10–20 v/v%. There are other carbon dioxide sources with different contents, and the influence of the flue gas composition is unknown, opening new avenues for further research. This was explored by Baena-Moreno et al. (2021) by upgrading biogas (commonly 40 v/v% carbon dioxide and 60 v/v% methane) with flue gas desulfurization gypsum waste, but with other process configurations which produced biomethane as an extra added-value chemical (Baena-Moreno et al. 2021).

The process proposed by this work can be seen in Fig. 7. The main difference to the previous works on top of the flue gas composition is indirect carbonation. The processes described by these authors captured first carbon dioxide from biogas with sodium hydroxide, producing sodium carbonate. In a second stage, sodium carbonate reacted with flue gas desulfurization gypsum waste to produce calcium carbonate and potentially other added value compounds (Baena-Moreno et al. 2021). This can be a potentially interesting strategy for industries with available excess of sodium hydroxide. Overall, precipitation efficiencies of 53.09–80.09% (66% average) were obtained (Baena-Moreno et al. 2021).

The carbonation of flue gas desulfurization gypsum waste has been evaluated. Albeit the low capture capacities, future studies could exploit other alternatives, such as gas–liquid carbonation routes. Given the quality of the calcium carbonate of the carbonation stage, the overall process is particularly interesting from a circular economy perspective.

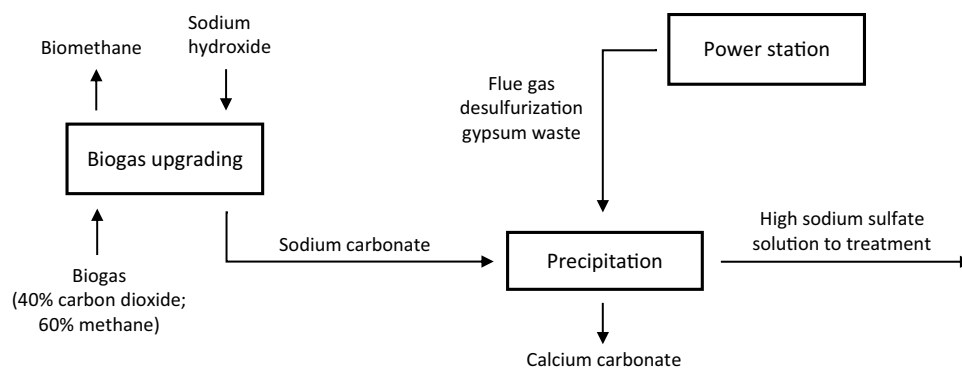


Fig. 7 Combined biogas upgrading and flue gas desulfurization gypsum waste carbonation. Carbon dioxide is captured from biogas with sodium hydroxide to form sodium carbonate. The sodium carbonate is later further reacted with flue gas desulfurization gypsum waste

to form calcium carbonate and sodium sulfate. The calcium carbonate precipitated has a calcite quality, while some post-treatments are needed to purify the sodium sulfate formed. Modified after Baena-Moreno et al. (2021)

Comparison of industrial effluents and residues

The authors have attempted to compare effluents and residues in terms of capture capacity, abundance, and potential final utilization for the carbonated products. However, we want to stress that the carbonation of the industrial effluents and residues was performed at different experimental conditions depending on the nature of the waste and the aims. The outcome is gathered in Table 6. Unfortunately, all capture capacities and worldwide production numbers were not retrieved including the absorption capacity of black liquor, as mentioned in the previous section.

For some of the wastes, worldwide production numbers were estimated based on data from the source of the waste for example for municipal solid waste incinerator ashes and cement waste. For calculating the range of production of municipal solid waste incinerator ashes, we used the production of 1.75 billion tons of municipal solid waste (MSW Management 2019), and the incinerated part (11%) (The World Bank - Data topic 2022), multiplied by the ash content (typically 1–30%) (Siddique 2010). According to a statistical database, the annual global production of cement has been 4.4 billion tons in 2021 (Statista 2022), and the waste cement kiln dust makes up approximately 15–20% of the total cement production. Out of the total production of kiln dust, 60–67% is recycled in the cement production process and the rest is left for other applications or mainly disposed in landfills (Kunal et al. 2012). This leftover was considered for the calculations presented here. However, estimates for paper mill waste and organic waste are excluded due to the lack of data.

It can be seen in Table 6 that there are clear differences between absorption capacities and abundances among the different wastes. For example, the highest absorption capacities were found for cement waste and flue gas desulfurization

gypsum waste, while the most abundant wastes seem to be mining waste and waste from municipal solid waste incinerator ashes. Importantly, the potential of each waste for carbon dioxide capture in terms of overall amount captured must be evaluated through a combination of the three parameters included in Table 6. For example, mining waste is very abundant albeit its limited capacity and the potential utilization of the final carbonated products needs to be explored.

Another example is flue gas desulfurization gypsum waste with a high capture capacity and a great commercial value of the carbonate but a low worldwide production. All these characteristics must be further evaluated with the help of decision-making tools such as economic evaluations and life cycle assessments. It must be noted that the carbonation pathway is different for each type of waste and therefore the process conditions vary as well. For example, in some cases high temperatures and pressures are required for the efficient capture of carbon dioxide, which entail an economic and environmental penalty. This analysis is out of the scope of the comparison presented here as it will require specific process design and analysis. This fact opens new avenues for further research in the path towards using waste for carbon dioxide capture via carbonation.

Conclusion

In this paper, potential effluents and residues from various industries for carbon dioxide capture available at industrial site are reviewed. Ten types of waste were included. The most influential studies were summarized, and potential process ideas were proposed for those wastes which could be used for carbon dioxide capture. The capture capacities for the different wastes differ widely depending on the

Table 6 Comparison of the wastes reviewed. The data gathered include the capture capacity range, potential products utilization, and global production. There are big differences among the wastes reviewed for the parameters above said. These differences can make some waste more suitable for carbon dioxide capture than others

Waste	Capture capacity range (kg per ton of waste)	Potential end life of final product	Worldwide production (millions of tons)	Reference for worldwide production
Steelmaking slag	Gas–solid: 10–50 Aqueous: 250–300 Indirect: 100–250	Could be potentially used as aggregates in concrete, asphaltic paving, fill, feed for cement kilns	170–250	Pacheco-Torgal et al. (2018), Joyce (2021)
Municipal solid waste incinerator ashes	Gas–solid: 20–120 Aqueous: 200–260	Feed for cement kilns or safety disposal for carbon dioxide storage	2000–57,000*	Estimated
Combustion fly ash	Gas–solid: 2–20	Use in concrete production	300–400	Dwivedi and Jain (2014)
Black liquor	Not evaluated	The lignin recovered to produce many different biochemicals. The carbonated formed for carbon dioxide storage	Approximately 1300	Kim et al. (2019)
Paper mill waste	218–460	Cement manufacturing, carbon dioxide storage	Data not available	
Mining waste	Approximately 130	Pacify hazardous waste, carbon dioxide storage	Approximately 100,000	The Conversation (2022)
Cement waste	Gas–solid: 81–800** Indirect cannot be evaluated	Reuse as additive in cement or concrete production, in soil stabilization	217–352*	Estimated
Construction and demolition waste	Gas–solid: 45–417	Carbonated recycled aggregates for reuse in concrete	2400–3600	Zhang et al. (2020a)
Organic waste	4.0–17.7	Production of valuable organic carbonates, or carbon dioxide storage	Data not available	–
Flue gas desulfurization gypsum waste	530–800***	Commercial calcite, cement manufacturing	Approximately 30	Lee et al. (herefore, using fly ash as a c2012b), Koralegedara et al. (2019)

*Value estimated from available data of raw materials

**Experiments carried out under humid conditions in contrast with the other wastes here reviewed. High values correspond to high humidity ratios

***Carbon dioxide captured via a different methodology in a two-stages process

characteristics of each manufacturing process and waste. The range is 2–800 kg of carbon dioxide per ton of waste.

Cement and flue gas desulfurization gypsum waste have the highest capture capacity per ton of waste. In addition, the worldwide waste production might have an overall potential for carbon dioxide capture. For example, municipal solid waste incinerator ashes and mining waste are very abundant but further studies are needed to develop processes increasing the capture capacity of these wastes. Future research must also consider the utilization of black liquor as a potential waste for carbon dioxide capture, as the capture capacity of this waste is not reported to date. We foresee that the data combined with the discussion provided here will accelerate and enhance the research on carbon dioxide capture and storage to reach the climate goals.

Authors' contributions Conceptualization was contributed by FMB-M, EL, DB. Data curation was contributed by FMB-M, EL. Formal analysis was contributed by FMB-M, EL. Funding acquisition was contributed by DB. FMB-M, EL, DB contributed to investigation. FMB-M, EL contributed to methodology. DB contributed to project administration. DB contributed to resources. DB contributed to supervision. AMR, JW-M contributed to validation. FMB-M, EL, DB contributed to visualization. FMB-M, EL, DB, AMR, JW-M contributed to roles/writing—original draft. FMB-M, EL, DB, AMR, JW-M contributed to writing—review and editing.

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Declarations

Conflict of interest Authors declare that we have no conflicts of interest or competing interests.

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Consent for publication Not applicable.

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