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Review

Prospect of Post-Combustion Carbon Capture Technology and Its Impact on the Circular Economy

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Abstract: The sudden increase in the concentration of carbon dioxide (CO_2) in the atmosphere due to the high dependency on fossil products has created the need for an urgent solution to mitigate this challenge. Global warming, which is a direct result of excessive CO_2 emissions into the atmosphere, is one major issue that the world is trying to curb, especially in the 21st Century where most energy generation mediums operate using fossil products. This investigation considered a number of materials ideal for the capturing of CO_2 in the post-combustion process. The application of aqueous ammonia, amine solutions, ionic liquids, and activated carbons is thoroughly discussed. Notable challenges are impeding their advancement, which are clearly expatiated in the report. Some merits and demerits of these technologies are also presented. Future research directions for each of these technologies are also analyzed and explained in detail. Furthermore, the impact of post-combustion CO_2 capture on the circular economy is also presented.

Keywords: post combustion; aqueous ammonia; activated carbons; ionic liquids; hydrogen gas (H_2); integrated gasification combined cycle (ICGC); circular economy

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1. Introduction

The population growth and the need for clean sources of energy in the 20th Century has surged tremendously in the last few decades. The sudden rise in industrialization in the 21st century has yielded increases in the population and demand for energy as well. Currently, nearly 90% of world energy demand is highly dependent on fossil products [1–3]. In spite of the fact that fossil-based products have contributed tremendously to industrialization, their effects on the environment cannot be ignored. The last few years have seen a sharp increase in the average temperature from the acceptable value of 0.6 to 1 °C [4]. For instance in 2014, 23% of carbon emissions into the atmosphere emanated from power plants fueled using fossil commodities [5]. It is being projected that by 2035 these values will further increase [6]. Renewable energy is considered as a possible replacement for fossil products; hence, the last few decades have seen the world earnestly encouraging its application in the electricity/power industry. Even though these appreciable increments are being encouraged, natural gas is projected to dominate the supply of power globally till 2030 [7]. These statistics are attributed to the fact that the capital costs involved in electricity produced from natural gas are low. Again, the carbon produced from the natural gas combined cycle is also very low as well [7]. It must be stated that the highest producers of CO_2 emissions often come from stationary plants powered using fossil commodities [8–12]. In terms of statistics, 60% of these carbon emissions are attributed to operations of thermoelectric power plants, steel mills, refineries, etc. [7]. Most thermal plants around the world are powered using coal. Coal is one of the largest contributing factors of global emissions. The distribution of greenhouse gas emissions by various sectors around the world is captured in Figure 1.

A sudden increase in anthropogenic activities based on the findings of the International Panel on Climate Change has caused the melting down of polar ice due to the ozone layer being depleted causing global warming as well as changes in climate [13]. The release of CO_2, nitrous oxide, methane, as well as water vapor has serious implications on the survival of the human race [11,14–16]. The major source of greenhouse gases originates from CO_2 which forms 76% of greenhouse gases in the atmosphere. These high values are attributed to the burning of fossil products in power plants [17]. Most data published in 2013 showed a surge in the CO_2 concentration into the atmosphere from 120 to 400 ppm volume. This shows clearly the need to find a lasting solution to this problem [18]. As a way to face the challenge relating to the global warming, the world formulated policies such as the Kyoto Protocol in 2005. The main idea behind this was to reduce the greenhouse gases, particularly CO_2, from 7 giga tons. This protocol was geared towards achieving these targets within some few decades from the day it was passed [19,20]. This urgent clarion call by the world in general has led to several academic studies being conducted to lessen the total gaseous release into the air globally. The pragmatic approach to reducing carbon emissions is to reduce the burning of the fossil commodities, rely on renewable energies that are sustainable and have low or no environmental impacts [21,22], consider efficient energy generation mediums [23–25] and/or alternatively consider energy sources with CO_2 capture and storage units [26]. Mitigation of CO_2 emissions from energy plants is one of the feasible routes for reducing toxic gaseous release based on a report by the United Nations Framework Convention on Climate Change. It therefore becomes imperative to consider strategies in which these carbon dioxide emissions could be captured from power plants [27–30]. From studies conducted by the International Energy Agency (IEA) and Organization for Economic Co-operation and Development (OECD), integration of carbon capture and storage (CCS) technology will aid in reducing overall CO_2 emissions by 14% [20].

CCS technology is perceived as the only solution for mitigating overall emissions into the atmosphere especially given fossil products continue to be the dominant source of energy generation. The idea is to absorb the carbon emissions from industry or other sources of energy generation. This can be orchestrated prior to the burning of the fossil product or after the burning of the product. This strategy again is normally followed by the compression of the carbon dioxide, transporting it to a safe place to store the gas and finally depositing it into the ground via a process called sequestration. This approach prevents the gas from mixing into the atmosphere [31]. The capturing of carbon dioxide is categorized into pre-combustion, post-combustion and oxyfuel combustion [2,32]. The possible alternative to the capturing of emissions from large power sources is via post-combustion capture technology. Capturing carbon dioxide from plants powered by fossil commodities contributed to 3/4th of the overall market price of the CO_2 capture. This method is energy intensive. The remaining 1/4th is attributed to the transportation as well as storage [33,34]. CCS technology can aid in the reduction in the cost of carbon capture as well as achieving the main objective of reducing emissions into the atmosphere [35]. Due to technological advancements, several strategies for post-combustion capture have emerged. These include membrane-based separation, cryogenic separation and physical and chemical absorption [36,37]. Chemical absorption is described as a proactive method of absorbing carbon dioxide because the process is very efficient and it has been applied in a number of industries over the last 60 years [38].

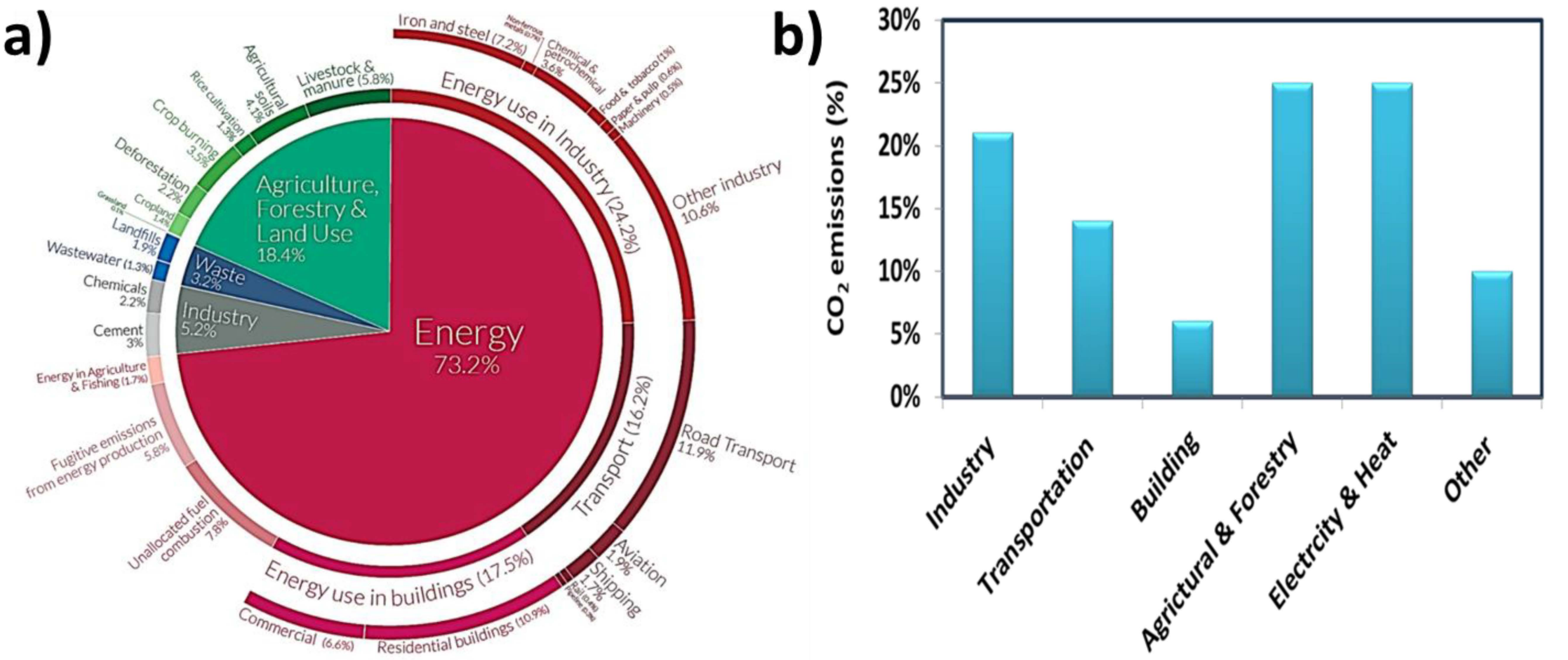


Figure 1. Carbon dioxide emissions by (**a**) various sectors (https://ourworldindata.org/emissions-by-sector, accessed on 1 September 2022) and (**b**) economic sectors (https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data, accessed on 1 September 2022).

For decades, most carbon capture technologies have utilized an amine-based chemical absorption method using mono ethanol amine in the elimination of CO_2 that is discharged from natural gas processing as well as power plants powered using fossil fuel. The cost of solvent regeneration for this technology is very high coupled with issues relating to corrosion of the equipment. There are also issues sometimes associated with the degradation of the absorbent. This implies that the major limitation with carbon dioxide capture using this technology is the energy penalty. Cryogenic distillation which is an equal alternative has some limitations because of the cost involved. These limitations have led to adsorption being investigated as the future of CCS technologies. It involves the application of solid sorbents made from cheap and abundant material making the entire capture process very affordable [39,40]. The research conducted in this area is primarily to develop solid sorbents that are durable by means of adding foreign particles in the separation process as well as carbon dioxide absorption via the application of activated carbon [41], zeolites [42], metal organic frameworks [43] and microporous polymers enriched with nitrogen [44,45]. Activated carbons have large surface areas, good thermal stability and excellent chemical resistance; hence, they considered as an efficient absorbent in carbon dioxide capture [46]. This investigation will therefore focus on some of the technologies used in the post-combustion capture of carbon dioxide as well as their impact on the circular economy, as seen in Figure 2.

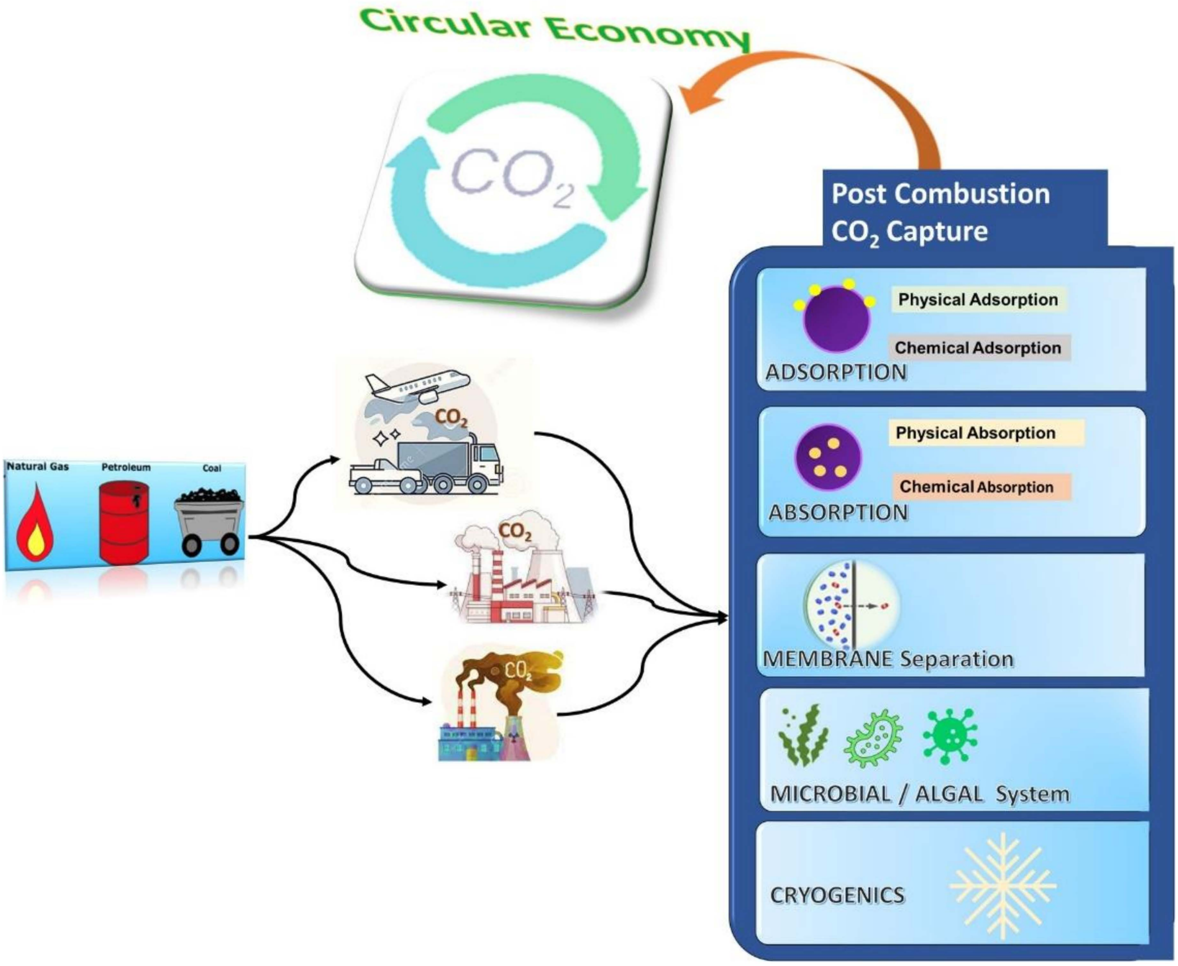


Figure 2. Scheme summarizes the main topics covered.

2. Existing Technologies for Capturing CO_2

CCS technologies are designed to absorb emissions from the atmosphere. The capturing process is often centered on the design of the power plant fueled using fossil products.

There are presently three main strategies as stated earlier and these include pre-combustion (PRC), post-combustion (PC) and oxy combustion (OC) capture technologies [47]. PRC implies the capturing of CO_2 in synthetic gas or fossil products before combustion takes place. The fuel is transformed to syngas which is composed of H_2 and CO. The separation process in this technology employs cheap physical solvents such as rectisol [48]. The OC method involves the fuel being ignited among highly purified O_2 and flue gas that is recycled producing CO_2 as well as water vapor. The CO_2 as well as the water vapor are then sequestrated [39]. In order to separate oxygen from air, more energy is required. The PC technology is considered as an optimum capture route because there is no need to modify the existent emission technology without any major changes. Figure 3 shows the processes involved in the three main carbon dioxide capturing technologies [49] while Table 1 defines the contrasts among these three categories of CCS technology.

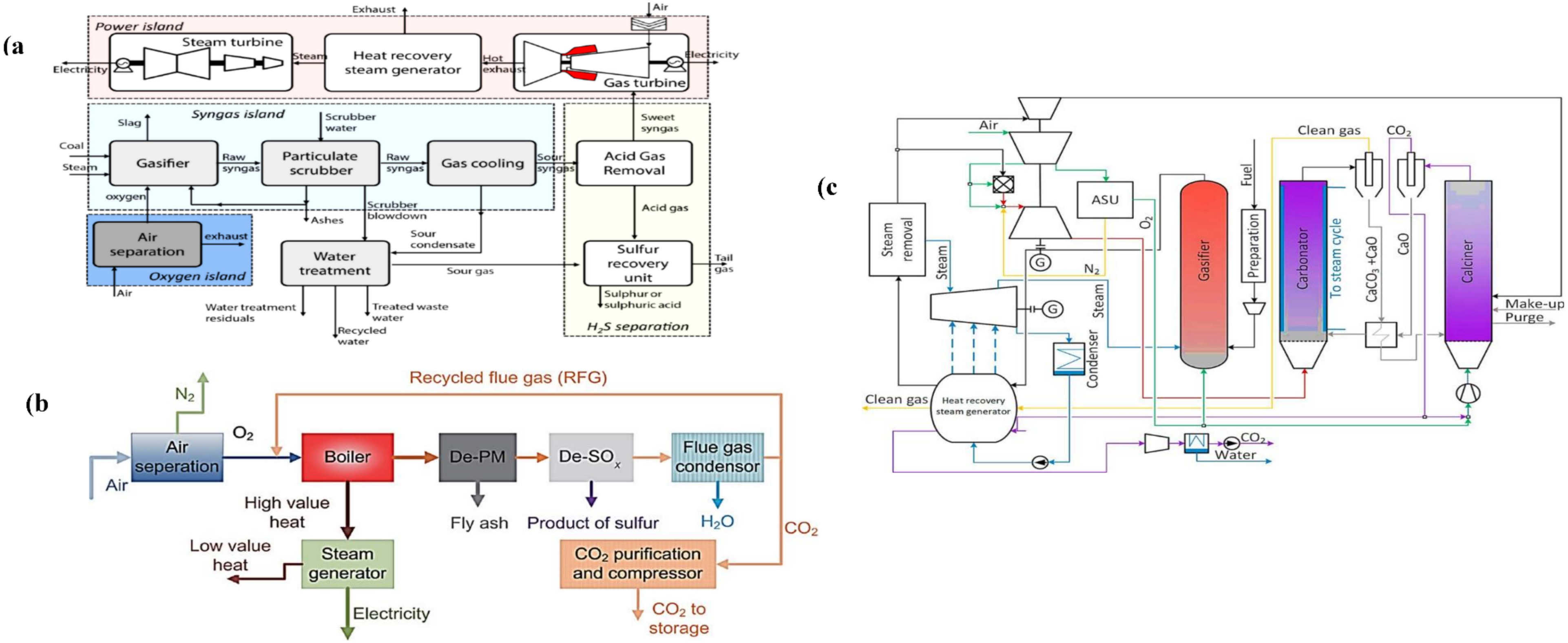


Figure 3. Carbon dioxide capture technology for:(**a**) PRC [50], reproduced with permission No. 5402050329104, (**b**) OC [51], open access, (**c**) PC [17], reproduced with permission No. 5402050963073.

Table 1. Comparison of various CO_2 capture approaches in terms of merits as well as demerits.

Technologies	Merits	Demerits	Ref.
Pre combustion (PRC)	• The capturing of carbon dioxide occurs at higher pressures enabling the production of carbon-free fuel. • Several hydrocarbon fuels such as natural gas, biomass, coal and petroleum can be utilized. • The dominant product of PRC capture is syngas which is ideal for the combined cycle. • The establishment of full-scale plants is under progress. • Energy conservation owing to a higher CO2 load, a higher pressure and a lower volume implemented. • It consumes less water than post-combustion technology.	• This method is capital-intensive with a high level of risk involved. • It is a complicated process because it involves fuel conversion before the burning of the fuel into syngas. • Lower efficiency of the hydrogen-based gas turbine plant of the integrated gasification combined cycle.	[52]
Oxy fuel combustion (OC)	• The approach allows pure carbon dioxide to be produced. • The purification of the gas stream is easy. • There is also a drop in the release of nitrous oxide during the OC process. Reducing NO_x will also support reducing the exit gas flow rate and this will lead to a reduction in the market price of all equipment used. • Storing energy is easy using cryogenic liquids. • Minimum hazardous emissions. • High efficiency. • Reduced size of equipment implemented. • Compatibility with different steam cycles without major modifications. • Reduced net power output.	• Management of the oxygen is the major challenge relating to this carbon dioxide capturing technology. • No full-scale plants are in operation yet. • Some technical challenges. • Possibility of corrosion. • Requirement for specialized installation to avoid leakage of air.	[53,54]

3. Capturing CO_2 Using the PC Approach

The ideal method for the capture of CO_2 from flue gas is via PC technology. The processing industry usually prefers this method. It is possible to reconstruct PC technologies to power plants operated using fossil commodities. Post-combustion technology also uses wet/dry adsorbents in the capturing of CO_2. The exhaust stream is treated before the burning process to limit the composition of other species such as sulfur oxide, nitrogen oxide as well as water vapor under the post-combustion capture technology [38]. These secondary species have a detrimental effect on the operation if untreated. Flue gases are kept under atmospheric conditions as well as between 50 and 150 °C [55]. This represents 10% as well as 15% of the carbon dioxide concentration [56]. For most thermoelectric power plants, post-combustion techniques are used in the capture of CO_2 from these plants. It involves the burning of the fuel in the production of flue gas as well as compression, transport as well as sequestration to obtain the carbon dioxide [57]. Figure 3c shows that gas from a power plant powered using coal undergoes a treatment process via PC technology. These gases at high temperatures flow via electrostatic precipitator (ESP) before exiting the boiler. Most material particulates in nature are removed at the electrostatic precipitator. From the electrostatic precipitator, the gas flows to the flue gas desulphurization

(FGD). In the FGD, lime stones are utilized to trap the sulfur oxide gas. Adsorptions, absorption and membrane separation are used in the treatment of the flue gas to eliminate the carbon dioxide [58]. In spite of all the merits associated with this technology, there are some technical issues that must be surmounted before they can become commercialized on larger scale. The academic community is currently carrying out several investigations to enhance the entire capturing approach including technology and cost. Table 2 shows some merits and demerits for the specific methods used for capturing CO_2 using the post-combustion approach.

Table 2. Merits and demerits of CO_2 capture via the PC capture approach and its techniques.

Post Combustion CO_2 Capture			**Strategies for Post Combustion Carbon Dioxide Capturing**			
Merits	**Demerits**	**Ref.**	**Strategy (Efficiency)**	**Merits**	**Demerits**	**Ref.**
• Best approach applicable to gaseous toxic emissions. • It is also very economical. • This method supports the reduction in greenhouse gases.	• The sorbents are suitable for concentrated streams to make the system efficient. • Ideal sorbent for PC for the capture of CO_2 is very limited.	[59–61]	Chemical solvent scrubbing (90%)	• Oldest approach. • High capturing efficiency (75–95%). • Possibility of solvent regeneration.	• Solvent regeneration requires high thermal energy. • Solvent is expensive • Equipment used undergoes corrosion. • Solvent degradation leads to toxic emissions.	[62]
• Easy to retrofit combustion technology without making any significant changes. • During maintenance, the plant can still be in operation and can still be regulated. • Higher thermal efficiency for the electricity conversion process.	• More energy is needed for the compression of the captured CO_2.	[63–67]	Physical adsorption (55–92%)	• Process is reversible. • Possible to recycle the adsorbent. • Adsorption efficiency is very high. • Resistant for long term use.	• Cooling and drying of the flue gas. • Carbon dioxide desorption requires a high amount of energy. • Some adsorbents require high temperatures. • Sorbent performances are influenced by NOx and SOx.	[68,69]
	• The system efficiency is dependent on adsorbent design. • In the capture of CO_2 using the PC capture technique, the gas is normally made up of CO_2/H_2 and CO_2/N_2. There are secondary species present that have an effect on the separation process.	[70–72]	Calcium looping (>75%)	• Energy efficiency loss is low. • Ideal for the cement industry.	• Attrition dependent on how hard the limestone is.	[73,74]

Table 2. *Cont.*

Post Combustion CO_2 Capture			**Strategies for Post Combustion Carbon Dioxide Capturing**			
Merits	**Demerits**	**Ref.**	**Strategy (Efficiency)**	**Merits**	**Demerits**	**Ref.**
• The application of activated carbon makes the entire process environmentally friendly. • Post-combustion technologies can be attached to industry emitters to support the reduction in carbon emissions.	• The operating conditions in terms of temperature are very low; hence, the sorbents are limited to only activated carbons and zeolites. • The carbon dioxide is absorbed from low pressure and low carbon dioxide content gas streams at elevated operating conditions between 120 and 180 °C containing impurities.	[41,75–79]	Membrane separation (Up to 90%)	• Separation of other gases. • Efficiency of the separating process is high.	• Water and SO_2 have an impact on the easy flow of the gas. • Compression equipment is expensive and requires a lot of energy. • Reduced carbon dioxide purity. • For larger facilities, the area of the membrane must be large enough.	[8]
• The application of activated carbon makes the entire process environmentally friendly.	• The operating conditions in terms of temperature are very low; hence, the sorbents are limited to only activated carbons and zeolites.	[75–77]	Captured using Algae and other living species	• Oil production via this medium can replace coal. • Competitive economically.	• Production of algae's products and markets • Method meets industrial requirements.	[80,81]

3.1. Research Activities in Post-Combustion Capture Technologies

There are presently many research activities being considered on global warming with the main focus on absorbing carbon dioxide from flue streams. These separation strategies are categorized into wet absorption, dry absorption, membrane separation, cryogenic distillation, dry adsorption, centrifugal separation as well as cryogenic distillation [41,82]. Most industries consider carbon dioxide separation as a giant step in the fight against global warming. The petroleum-based industries usually employ PC systems for CO_2 scrubbing. The capturing of CO_2 involves a physical or chemical adsorption strategy as shown in Figure 4.

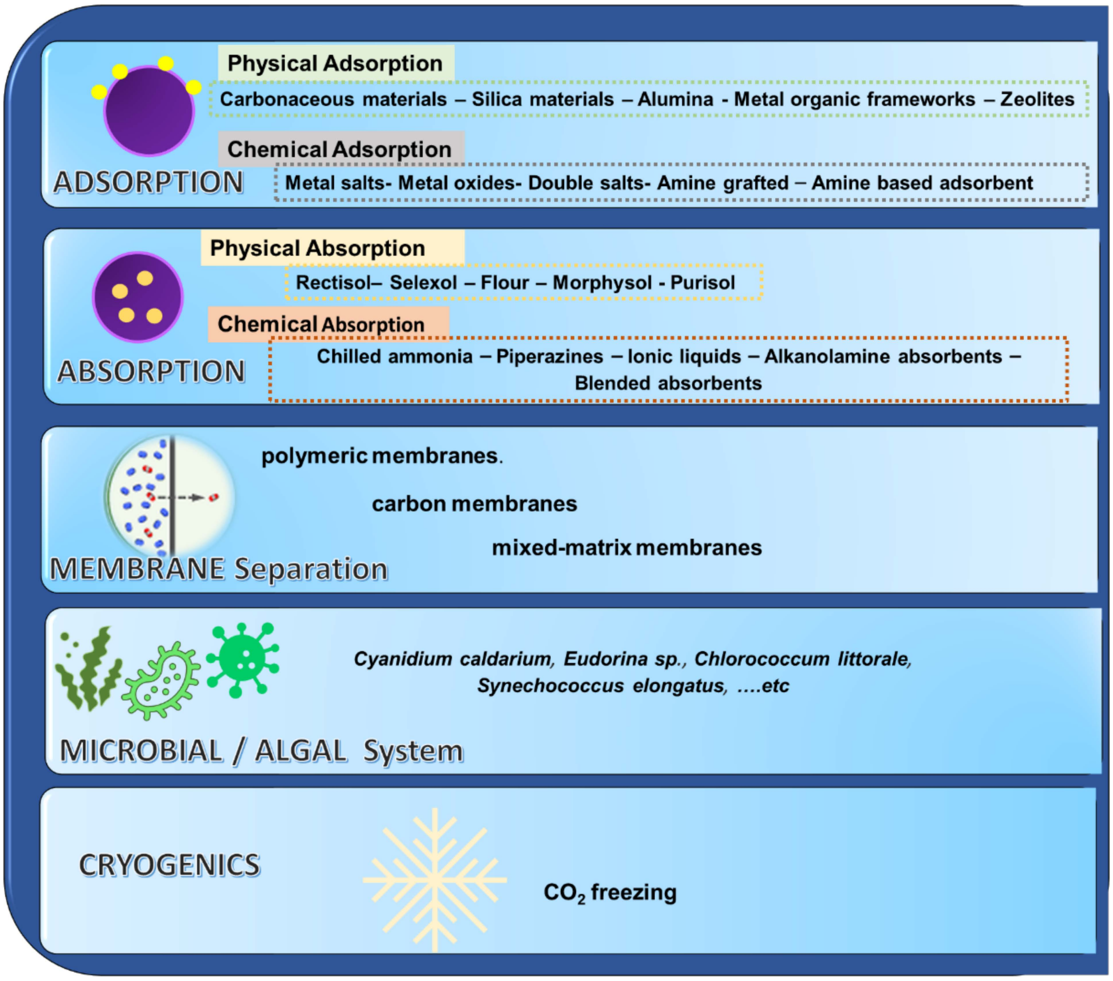


Figure 4. Post-combustion capture technologies.

Amine-based regenerative chemical adsorption is considered as a viable chemical adsorption method for large emission volumes from combustion producing concentrated carbon dioxide. It is also described as an optimum method for changing the density of the CO_2 from the literature [83,84]. Solvent regeneration in relation to the capturing of carbon dioxide using amine-based solvents is the major obstacle as the energy utilized is huge. This means that the entire process consumes more auxiliary power, making the system very expensive [47,65,85]. There are other challenges such as using heated absorbents, material erosion, slow solid–gas reactions, energy intensity and oxidative degradation of the amine [86]. Carbon dioxide absorption capacity is reduced when the amine compound degrades and accumulates. Injection of a new absorbent is required to salvage the situation but this increases the total cost of the technology. Again, the fact that the amine compound is volatile in nature also results in the chemical as well as the water evaporating and this often enters the flue gas which is clean. The process leads to amine gas being released and this eventually affects the ecosystem. The research community, in order to mitigate the challenges relating to chemical adsorption, has performed several studies by considering different materials.

Carbon dioxide separation using membranes utilizes ceramic-based materials and mixed matrix membranes for the capturing of CO_2. Poly ethylene oxide ceramics are also used to support the permeation of the carbon dioxide [87,88]. The physical as well as chemical behavior of the membrane affects the separation of these gases. Other factors such as the diffusion of the molecules of the gas in the membrane as well as the gradient in the pressures of the gases also have an effect on the gas separation [89]. The consumption of energy is very low in membrane-based separation. Cryogenic carbon dioxide separation involves the cooling of the CO_2 as well as the condensation of the gases. CO_2 is therefore eliminated due to this approach. The initial capital costs for this technology are very low and it is considered as an ideal PC technology, though its application on a larger scale remains a challenge. The amount of impurities using cryogenic separation makes them unattractive in its application in PC technology [90,91]. Again, the pressure of the CO_2 at exhausts from boilers powered using coal or natural gas is reduced. More energy is needed for refrigeration during cryogenic separation; hence, the method is not viable for larger plants economically. Today the world has made progress through research activities and has been able to develop a post-combustion capture process that is cheap with fewer technical issues in separating the CO_2 from the flue gas [92]. PC carbon capture techniques through a solid adsorbent using the pressure or thermal swing approach in separating carbon dioxide has been described in the literature as a replacement for the amine scrubbing process, as shown in Figure 5 [93]. By means of thermal or pressure modulation, there is a reduction in the regeneration energy requirement when the adsorption technique is used. The adsorption method tends to reduce the entire maintenance required [94,95]. Factors such as the adsorption capacity, stability and durability of the adsorbents and the regeneration of the adsorbed carbon dioxide have an effect on this method.

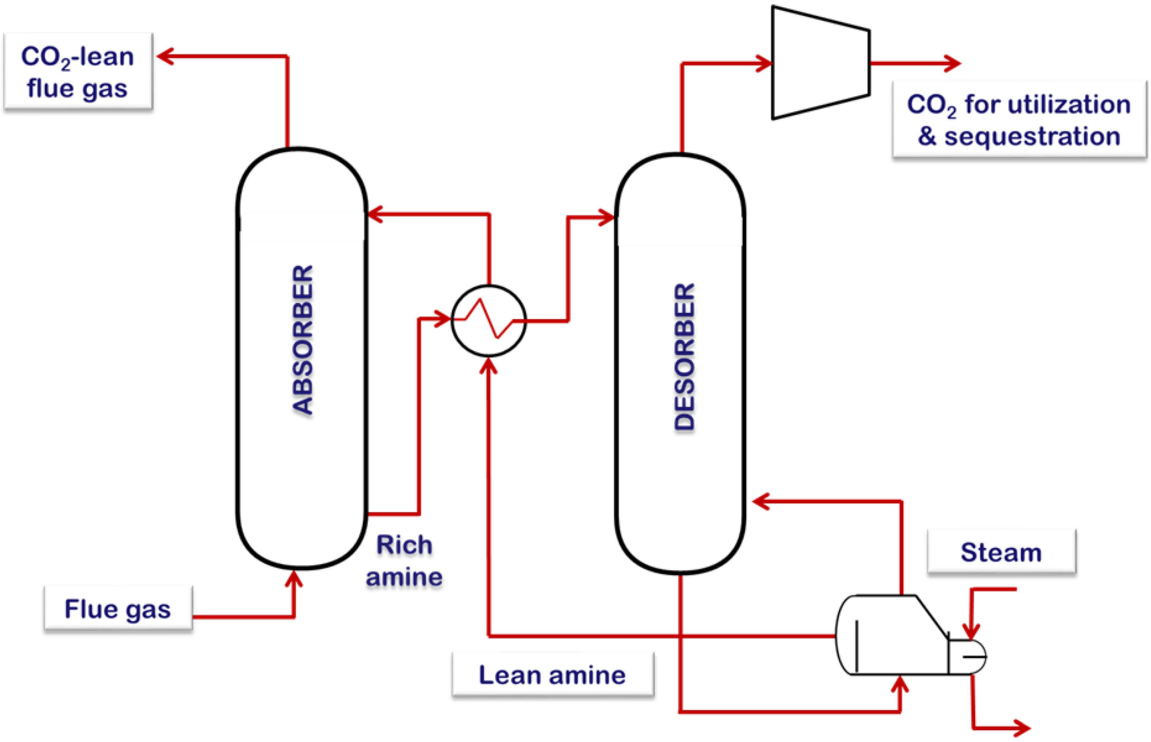


Figure 5. Amine-based scrubbing process [93], reproduced with permission No. 5402051268283.

The techno-economic evaluation of a single-stage pressure–vacuum swing adsorption (PVSA) cycle for post-combustion CO_2 capture assuming zero-cost sorbent was applied. At the optimized sorbent properties, the CO_2-avoided cost for PVSA varied from USD 86.8 (inlet CO_2 3.5 mol%) to USD 10.36 (30 mol%) for each ton of CO_2 avoided. The costs of the MEA-based absorption process, utilizing heat from a natural gas plant, were USD 76.53 and USD 54.61 per ton of CO_2 avoided, respectively, showing that PVSA is more economical for flue gas streams containing higher concentrations of CO_2 [96].

3.1.1. Adsorption Mechanisms for CO_2 Capture Using Activated Carbons

The best approach for the capture of CO_2 under atmospheric pressure as well as temperature is using activated carbons. A material that is carbonaceous with a high energy content but low in ash is utilized in the manufacturing of numerous activated carbons. The raw precursors utilized must be activated and must also have a low rate of degradation [97,98]. This means that material selection is very important during the production of activated carbon. Carbons, H_2 and O_2 have a direct impact on the physiochemical characteristics of the material. According to the literature, the kind of the precursor used has an impact on the adsorptive characteristics of activated carbon. The properties of the synthesized activated carbons are affected when carpet wastes are used as precursors. This is due to the fact that these wastes vary in terms of chemical composition. Pre-consumer waste tends to have a higher volatile matter, but the carbon yield is very low compared to post-consumer waste. The material structures are often rearranged during the devolatilization stage. This results in mass loss as well as the shrinking of the precursors because of moisture contents released via convection and diffusion [99,100]. The high incombustible ash content accounts for the high yield. Waste generated from the domestic environment as well as the street usually has an area ranging from 326 to 466 m^2/g [101,102]. The conditions surrounding the production of activated carbons have an impact on the kind of activated carbon developed. The activation process is categorized into two processes, i.e., physical and chemical activation.

Physical-Activated Carbons

Physical-activated carbons are manufactured through carbonization, which is often called pyrolysis, followed by activation [103–105]. Volatile matters as well as foreign materials are eliminated during the carbonization stage which involves the process being conducted in the presence of nitrogen. The operating temperature that leads to carbonization is nearly 800 °C and this according to the research is ideal for the devolatilization. The char that is produced after this process then undergoes the activation stage via an oxidizing gas around 800–1000 °C [106]. Other investigations that have explored the capture of carbon dioxide at a pressure of 1 bar are captured in Table 3.

Table 3. Investigations on activated carbon produced purposely for carbon dioxide purification under atmospheric conditions.

Precursors	**Carbonization Approach**			**Activation Stage**				**Total Area (m^2/g)**	**Adsorption (mmol/g)**			**Ref.**
	Flow Rate (mL/min)	**Temp. (°C)**	**Retention Time (min)**	**Oxidant**	**Flow Rate (mL/min)**	**Temperature (°C)**	**Retention Time (min)**		**0 °C**	**25 °C**	**100 °C**	
Tobacco stem	-	180	600	KOH	-	500 600 700 800	240	786 1086 1922 2399	4.76–7.98	3.31–4.84	-	[107]
Bamboo	-	500	90	KOH	-	603	90	528		4.5	-	[108]
Shell of almond	-	-	-	Carbon dioxide	100	750	240	862		2.7	0.9	[109]
	-	600	-	Carbon dioxide	50	400 600 800 900	120	8 91 326 350		0.16 0.15 0.20 0.08		[110]
Olive stone	-	-	-		100	800	360	1215		3.1	0.8	[109]
Shell of coconut	-	-	-		140	800	210	1327		3.9	-	[111]
Coffee	50	600	-		15	800	-	590		2.35	-	[112]
Nut	500	600	60		500	900	61	570		3.49	-	[49]
Cotton	-	600	-		-	900	-	610		2.30	0.5	[113]
Tobacco stem	-	180	600	$Zn(NO_3)_2.6H_2O$	-	910	120	340–998	92–209 mg/g	66–145 mg/g	-	[114]

From the literature, it is clear that investigations using activated carbons for CO_2 capture have gained much attention in recent times. Equations (1) and (2) show the endothermic reactions between oxidizing gases and carbonaceous materials [115].

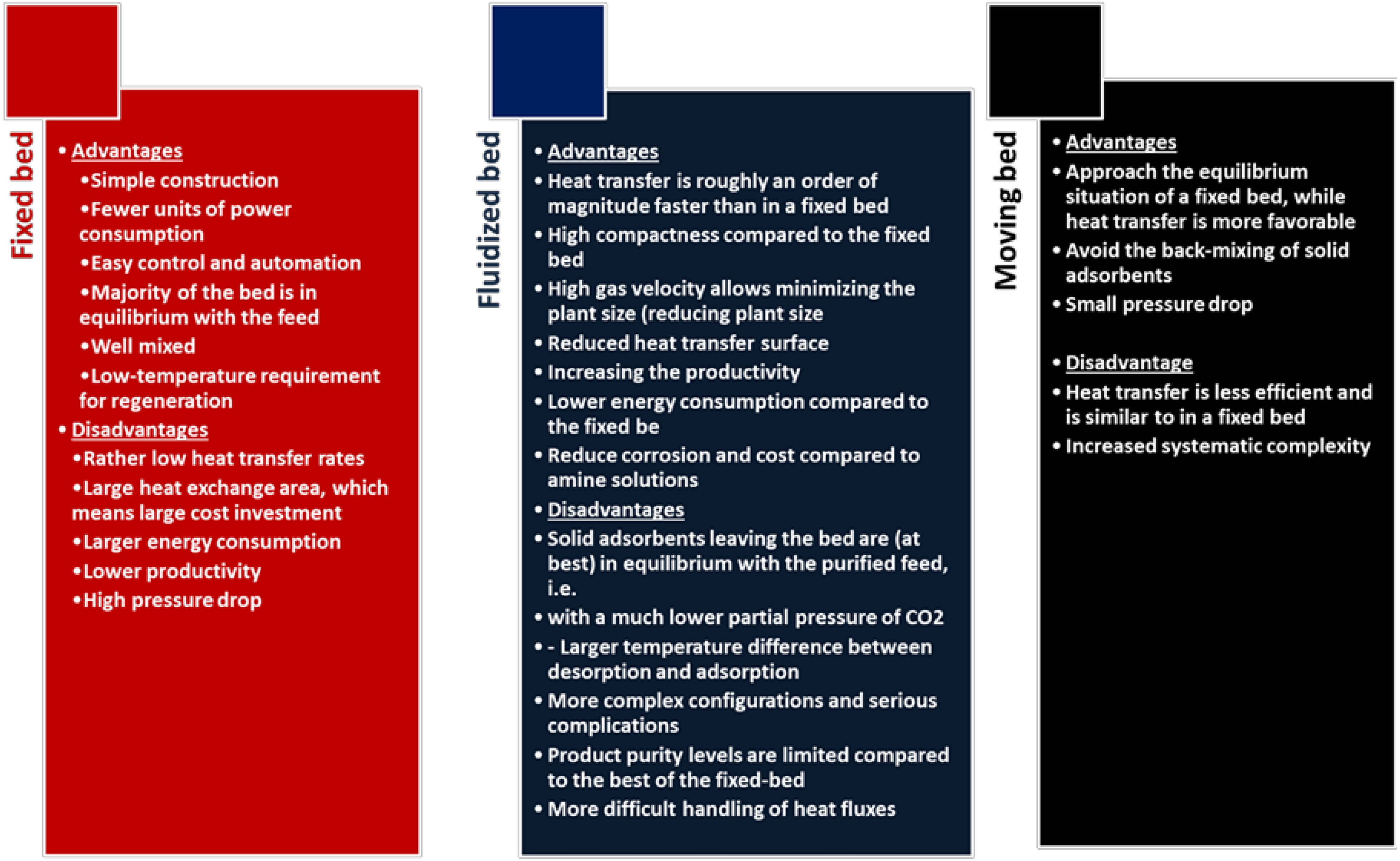
$$C + CO_2 \rightarrow 2CO \quad \Delta H = +173 \frac{kJ}{mole} \tag{1}$$

$$C + H_2O \rightarrow CO + H_2 \ \Delta H = +132 \frac{kJ}{mole} \tag{2}$$

The formation of micro-pores that are narrow often occurs when CO_2 is utilized as an activation agent. This is good for the adsorption of CO_2 [116] compared to steam. Steam has a high reactivity rate and can perform better within a low temperature range and a varying operational time. When the reactivity rate of steam is high, the steam will usually have small molecules compared to carbon dioxide. The carbon dioxide which is large in terms of molecular size aids in the rapid diffusivity to the micro-pores which results in an increase in the size of the micro-pores to form meso-pores as well as macro-pores [117]. This implies that carbon dioxide is therefore ideal for gas adsorption. The importance of using narrow micro-pores has also been investigated in the literature for adsorbing carbon dioxide because CO_2 creates spaces for the carbon dioxide molecules. Carbon dioxide activation is simple as well as cheap because the CO_2 flow is often regulated from a cylinder without any steam generator required [108]. There are a few challenges regarding the application of physical activation in terms of energy penalties because of the dual thermal–cooling routes as well the additional time is needed to finish the entire process [118]. The activation process occurs at higher temperatures around 1000 °C and this results in the carbon yield being reduced and not ideal for industrial purposes [119]. It therefore becomes necessary for an alternative to physical activation to be considered [120]. From the literature, it is clear that the use of single step carbon dioxide activation can lead to issues relating to longer operating hours and reduce the amount of energy being consumed. Nearly 1.79 mmol/g is adsorbed when the synthesized carbon produced from one activation step is used [121–123].

Chemically Activated Carbons

Chemical activation methods occur via the impregnation of precursors using a dehydrating agent before the carbonization or activation process. Salt mediums, acidic and alkaline are some commonly used dehydrating agents for this process. The sudden rise of research activities in this area is due to the fact that the amount of energy consumed is low when this method is used. The activation temperature for chemical-activated carbons is between 600 and 800 °C. Again, the operational time is very low and this tends to increase the carbon yield. The chemical activation process is executed usually as a single stage and this indicates that carbonization and activation are conducted in the presence of an activator. Porosity is created via dehydration and oxidation reactions [124]. Chemically activated carbons also go through some washing processes in order to eliminate any residual chemicals present as well as foreign matters in the form of carbon structures. These impurities usually result in secondary pollution due to the dehydration of the chemical agents [125,126]. In spite of chemical activation being a single step, investigations involving two stages are also being conducted. The dehydrating chemicals form a mixture with synthesized char [127]. Mixing the activating agents using raw precursors is not enough to produce activated carbon due to challenges in the penetration of the activator to the structures interiorly. When char is utilized, there is a development of pores during carbonization [128]. In order for the entire process to be cheap, the one stage activation process is considered the best compared to the two-stage process. Chemical activation also comes as solid–solid physical mixing or the wet impregnated method [129–131]. Three main reactors are used for PC carbon capture using adsorption: fixed bed, fluidized bed and moving bed. A comparison of the three main reactors is illustrated in Figure 6. Table 4 shows that Chemical-activated carbon produced for CO_2 capture under atmospheric conditions.



Fixed bed

- Advantages
  - Simple construction
  - Fewer units of power consumption
  - Easy control and automation
  - Majority of the bed is in equilibrium with the feed
  - Well mixed
  - Low-temperature requirement for regeneration
- Disadvantages
  - Rather low heat transfer rates
  - Large heat exchange area, which means large cost investment
  - Larger energy consumption
  - Lower productivity
  - High pressure drop

Fluidized bed

- Advantages
- Heat transfer is roughly an order of magnitude faster than in a fixed bed
- High compactness compared to the fixed bed
- High gas velocity allows minimizing the plant size (reducing plant size
- Reduced heat transfer surface
- Increasing the productivity
- Lower energy consumption compared to the fixed be
- Reduce corrosion and cost compared to amine solutions
- Disadvantages
- Solid adsorbents leaving the bed are (at best) in equilibrium with the purified feed, i.e.
- with a much lower partial pressure of CO2
- - Larger temperature difference between desorption and adsorption
- More complex configurations and serious complications
- Product purity levels are limited compared to the best of the fixed-bed
- More difficult handling of heat fluxes

Moving bed

- Advantages
- Approach the equilibrium situation of a fixed bed, while heat transfer is more favorable
- Avoid the back-mixing of solid adsorbents
- Small pressure drop

- Disadvantage
- Heat transfer is less efficient and is similar to in a fixed bed
- Increased systematic complexity

Figure 6. The merits and demerits of the fixed bed, fluidized bed and moving bed reactors.

Table 4. Chemical-activated carbon produced for CO_2 capture under atmospheric conditions.

Precursors	**Stages**	**Activation Stages**						**Area**	**Adsorption Capacity (mmol/g)**				**Ref.**
		Activator	**Impregnation ratio (wt/wt)**	**Temperature (°C)**	**Heating rate (°C/min)**	**Time (hour)**	**Flow rate (mL/min)**	**(m^2/g)**	**0 °C**	**25 °C**	**50 °C**	**75 °C**	
Wood	1	H_3PO_4	2:1	450	4	1	N/A	1889	-	2.9	-	-	[132]
Palm stone	1		2:1	450	1	2	80	1320	3.1	-	-	-	[133]
Palm stone	1	$ZnCl_2$	2:1	500	1	2	80	924	2.7	-	-	-	[133]
Rice	1		1:1	501	15	2	101	928	-	2.3	-	0.5	[134]
Bagasse	1	KOH	1:1	500	10	1	100	923	-	1.7	-	0.6	[134]
Ash	2		5:1	700	5	2	N/A	161	-	0.6	-	-	[135]
Saw dust	2		4:1	700	5	1	N/A	1643	8.0	4.8	-	-	[136]
Yeast	2		1:1	600, 700, 750	N/A	1	50	1348	-	1.3–4.77	0.94–3.4	0.77–2.4	[137]
Shell of peanut	2		1:1	700	5	1.5	120	956	5.2	4.0	-	-	[138]
Cellulose	2		2:1/4:1	600–800	3	1	-	2370	5.8	3.5	2.2	-	[139,140]
Starch								2190	5.6	3.5	1.8	-	
Microalgae and glucose			1:1, 2:1 or 4:1	650 and 750	-	24	-	1940	5.9–6.4	3.5–4.5	2.2–2.8	-	[141]

3.1.2. Chemical Absorption Using Aqueous Ammonia

Chemical absorption involves capturing carbon dioxide using an alkali solution [38,142]. The process involves a neutralization reaction where an alkaline solution is utilized as an absorbent in order to go into a reaction with the CO_2 as well as forming carbonate or bicarbonate [143,144]. Alkaline solutions that are very strong as well as weak are commonly used as absorbents. Some alkaline solutions include potassium hydroxide and sodium hydroxide as well as alkaline solution [145,146]. Strong alkaline solutions are very corrosive to equipment. Some common alcohol amines such as diethanolamine (DEA), triethanolamine (TEA), N–methyldiethanolamine and monoethanolamine (MEA) have some demerits of requiring high energy for regeneration [147]. These alcohol amines also undergo degradation [148]. Today, aqueous ammonia is considered as the best replacement for alcohol amine because it has a high absorption efficiency. It also has a high absorption capacity but the energy required for absorbent regeneration is very low. Aqueous ammonia is also ideal for the production of fertilizer to enrich the soil. However, it is easy to eliminate other contaminants that may be present such as SO_2, NO_X and mercury, as shown in Figure 7.

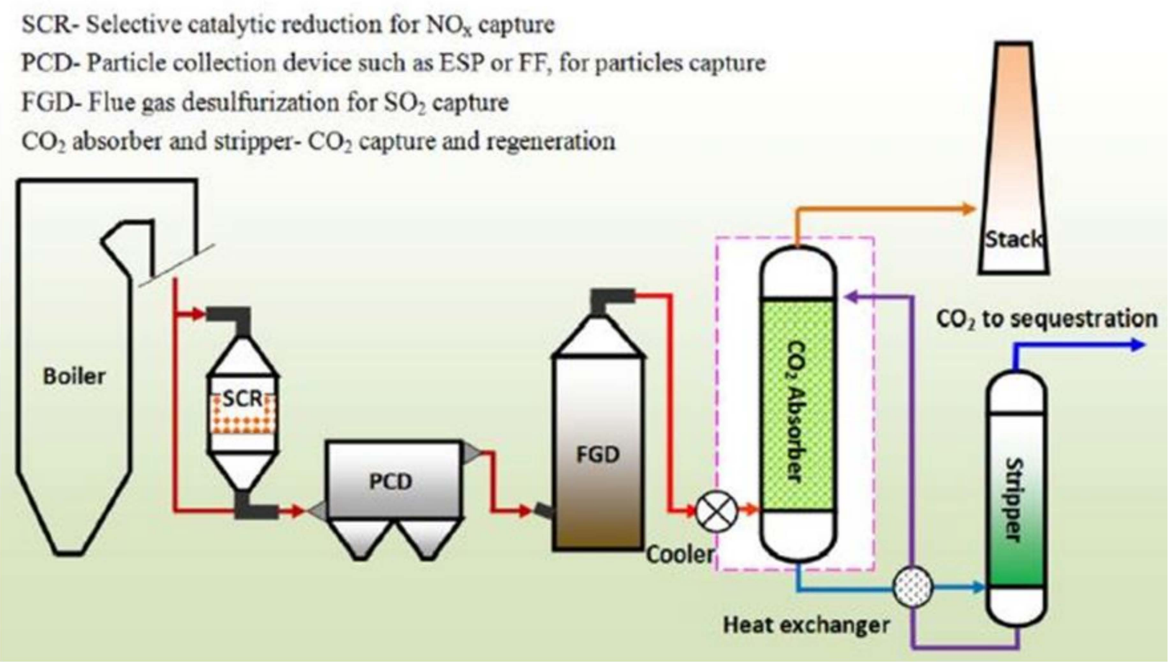


Figure 7. Capturing of carbon dioxide using aqueous ammonia [149], reproduced with Permission No. 5402051461114.

The sudden increase in CO_2 capture using aqueous ammonia can be attributed to its advantages over other CO_2-capturing techniques. Most research conducted in this area is quite limited [149,150]. The method for absorbing CO_2 via aqueous ammonia involves several physiochemical stages that are quite complex and usually involve temperature, pressure and turbulent conditions [151]. The reactions leading to the capturing of CO_2 via aqueous ammonia are illustrated in Equations (3)–(6).

$$2NH_3 + CO_2 \leftrightarrow NH_2COONH_4 \tag{3}$$

The next stage involves the hydrolysis of NH_2COONH_4

$$NH_2COONH_4 + H_2O \leftrightarrow NH_4HCO_3 + NH_3 \tag{4}$$

NH_3 undergoes hydrolysis

$$NH_3 + H_2O \leftrightarrow NH_4OH \tag{5}$$

$$NH_4HCO_3 + NH_4OH \leftrightarrow (NH_4)_2CO_3 + H_2O \tag{6}$$

$$(NH_4)_2CO_3 + CO_2 + H_2O \leftrightarrow 2NH_4HCO_3 \tag{7}$$

$$NH_3 + CO_2 + H_2O \rightarrow NH_4HC \tag{8}$$

Reaction Leading to the Capture of CO_2 Using Aqueous Ammonia

Figure 8 explains the chemical species as well as the phase equilibrium in $NH_3 - CO_2 - H_2O$. From the reaction mechanism, NH_2COO^-, HCO_3^- and CO_3^{2-} must coexist, implying that the products from the reaction will be NH_2COONH_4, $(NH_4)_2CO_3$, NH_4HCO_3. Reaction time and operational conditions such as time and pressure have a direct effect on the carbon dioxide absorption using ammonia [152]. Ammonia in excess at the early stage of the reaction leads to carbamate formation. The final stage of the reaction results in bicarbonate being formed as the main species.

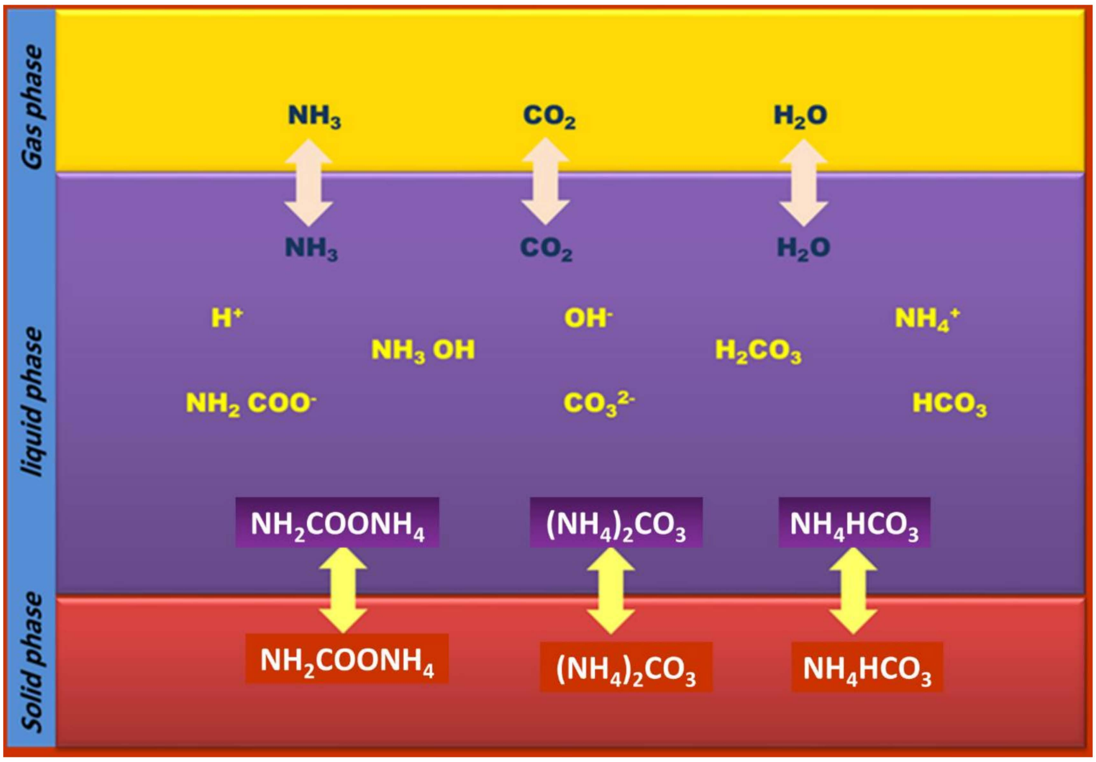


Figure 8. Three phase system for the chemical species leading to CO_2 absorption using aqueous ammonia [149], reproduced with permission No. 5402060371835.

Once the critical reaction time is reached, carbamate transforms to bicarbonate. Throughout the entire process, carbamate in terms of concentration is usually higher than that of the carbonate [153,154]. According to an investigation conducted, during the initial stage of the reaction, the formation of carbamate dominated the overall process. Bicarbonate only comes in after some time [38,155]. The stages leading to the capture of carbon dioxide using ammonia include the formation of carbamate as well as the transformation of carbonate [156–158].

The techno-economic evaluation of alkali–metal carbonates, chilled ammonia, calcium looping and membranes was compared to MEA as the post-combustion CO_2 capture technologies in a pulverized-coal power plant, concerning the cost indicators and efficiency penalty (cost of electricity, net CO_2 capture rate, net plant efficiency, net power output, capital costs, and cost of CO_2 avoided). Calcium looping technology recorded the lowest efficiency penalty (4.6%-points) and cost of PCC (36.3% increase in levelized cost of electricity). Moreover, employing calcium looping for post-combustion CO_2 capture lowered the cost of CO_2 avoided up to 29 USD2010/tCO_2. Hence, the performance of calcium looping is superior to the MEA process [159]. The techno-economic performances of magnesium and calcium-based sorbents utilized for post-combustion CO_2 capture in high temperature solid looping cycles located in a fossil power production plant with a total electrical capacity of 1000 MW and CO_2 capture rate 90% were studied. The net power efficiency of the calcium looping cycle was 1–1.4 net percentage points higher than that of magnesium and both of them were lower than that of natural gas combined system by 4–6% points. According to the key economic indicators (CO_2 capture cost and electricity production cost, etc.), it was found that the carbonate-based systems performance was higher than that of the amine-based system [160].

3.1.3. Post-Combustion CO_2 Capture Using Nano Materials

Materials with dimensions less than 100 nm are considered nano materials [161]. During the synthesis of the material into a nano scale regime, several size-dependent properties such as adsorptive property also become affected [162]. Nano materials usually have a low density and are smaller in size and have a good surface area, hence making them suitable materials for carbon dioxide adsorption [162].

Nano Porous Materials

Materials with pores between 1 and 100 mm are classified as nano porous materials [163]. They tend to have a higher area compared to materials that are not porous. Nano materials are usually preferred because their pore size as well as structure can be designed to support the adsorption process [164]. Activated carbons as well as zeolites which are non-porous have been used for the capture of CO_2 over a period of time in the last decade. A molecular basket was designed via grafting polyethylenimine (PEI) evenly on MCM–41 [165]. The wet impregnation method was adopted in the preparation of the sorbent and this involved mixing MCM–41 and PEI in a methanol medium. The next stage involved the drying of the mixture. The molecules of the carbon dioxide were trapped by the polyethylenimine doped in MCM–41 mesopores. The adsorption process was geared towards the carbon dioxide but there was some form of stability throughout the adsorption/desorption cycles. The size of the pores of MCM–41 was also enhanced by another group of researchers during the grafting of an amine-based functional group [166,167].

Nano Structured Hollow Materials

Some materials have a shell and a core; hence, they are referred to as hollow structured materials [168]. Materials that are synthesized in a nano regime form nano hollow structured materials. These materials are characterized by changes in the chemical properties of the compounds [168]. The commonly used type of hollow structured materials are carbon nano tubes (CNTs) and their diameter falls within the ranges of 1–10 nm. Again, in terms of length, they fall within 200–500 nm [169,170]. CNTs have been used in the capture of carbon dioxide. The investigation analyzed the interaction between molecules of CO_2 as well as CNTs [171]. The walls of the CNTs were carbon dioxide–philic compounds where the carbon dioxide established a strong attraction with the walls of the CNTs instead of with other carbon dioxide molecules. A concentrated carbon dioxide environment was developed in the hollow core of the CNTs. Carbon dioxide capture using single-walled CNTs were also investigated by Cinke et al. [172]. Physical adsorption was the main activity carried out and the capacity of the adsorption decreased. It was also established that purified single-walled CNTs had a better adsorbing rate of carbon dioxide compared to unpurified single-walled CNTs. The use of multi-walled CNTs for CO_2 adsorption from a flue gas stream has also been investigated [173,174]. Desorption was carried out via thermal regeneration because the carbon dioxide adsorption process was considered an exothermic process. Performing the regeneration in vacuum conditions reduced the desorption duration. Multi-walled CNTs exhibited stability for 20 cycles of adsorption. Calcium oxide is also another material that has been designed in nano hollow structured form. The major challenge is that the sorbent tends to decay throughout multiple absorption as well as desorption cycles. This set back is attributed to the sintering effect [175], the increase in reactant absorbent and high temperatures [176]. From the literature, a novel structure of pod-like nano-sized calcium oxide hollow particles for the capture of carbon dioxide has already been developed [177]. This design strategy enhanced the stability of the calcium oxide from decay-related challenges. The method involved the preparation of calcium carbonate nanopods via a precipitation method as carbon dioxide was bubbling via calcium hydroxide slurry in a polymer block. Calcination of the produced calcium carbonate resulted in calcium oxide being formed.

Nanocrystalline Particles

Crystalline particles synthesized under the nano regime are nanocrystalline particles. Materials in the nano region are able to chemically absorb more molecules, particularly organic molecules [178]. The capturing capacity for carbon dioxide using a sorbent with varying particle sizes has also been investigated. The outcome of the investigation was that the tetragonal phase as well as the small size particle showed good characteristics in terms of absorption [178]. Li_2ZrO_3 is a tetragonal nanocrystalline material used in an investigation from the literature. The carbon dioxide captured during this process also increased [179]. Within a period of 5 min, the Li_2ZrO_3 exhibited a 27 wt% absorption capacity in comparison to commercialized Li_2ZrO_3 which requires 1440 min to support 18 wt% absorption capacity. Other researchers showed similar outcomes of their investigation using lithium silicate nanoparticles via sol–gel approach [180]. The synthesis of lithium silicate nanoparticles produced nanoparticles with size between 4 and 12 nm. The carbon dioxide absorption was stated as being 5.77 mol CO_2/kg sorbent around 610 °C. Removal of flue gas using packed bed lithium silicate pellets was also investigated in the literature. The investigation showed an absorption capacity of 5.0 mol CO_2/kg at 600 °C which was less than the lithium silicate nanoparticles [181]. Addition of inert $MgAl_2O_4$ to calcium oxide improved the stability as well as the sustainability of the calcium oxide [77,182,183].

4. Comparing Various Types of Sorbents for Post-Combustion CO_2 Capture

Corrosion, foaming, etc., continue to pose a threat to a number of industries in terms of carbon dioxide post combustion capture; hence, dry-based sorbents are being considered as suitable options to salvage this situation. These types of sorbents are very easy to handle and come with very limited challenges during operation. Investigations into this field are classified as inorganic or organic sorbents. Metal compounds are classified as organic. Alkali metal compounds as well as alkaline earth metals have all been studied [184–189] and their reactions are shown in Equations (9)–(11). This also shows that when the solvent is dry, it tends to have a higher affinity for carbon dioxide capture compared to liquid sorbents.

$$Li_4SiO_4 + CO_2 \leftrightarrow Li_2SiO_3 + Li_2CO_3 \tag{9}$$

$$Li_2ZrO_3 + CO_2 \leftrightarrow Li_2CO_3 + ZrO_2 \tag{10}$$

$$XO + CO_2 \leftrightarrow XCO_3 \tag{11}$$

5. Impact of Post-Combustion CO_2 Capture on the Circular Economy

The term circular economy refers to the transformation of wastes or products at the end of their lifetime into new resources for other purposes which minimizes the developed wastes and closes the loops in the different ecosystems. This occurs via different routes including reuse, recycle, repair and remanufacture. Shifting to a circular economy will simultaneously reduce greenhouse gas emissions by up to 70%. The circular economy obeys two main business models: promoting the extension of the lifetime of the materials via reuse, repair, and remanufacture, and the second model which focus on transforming wastes and old products into new resources via recycling [190]. Recently, the carbon circular economy has gained much interest owning to climate change which is a major global challenge. The reported change in climate has caused increases in the average temperature worldwide, elevation of the sea level, erosion of coastal region, acidification of oceans, disruption of water cycle as well as negative impacts on ecosystems, human welfare, etc. [191]. On the other hand, the reduction in CO_2 emissions or de-carbonization of the energy sector needs a significant transformation that will ensure the introduction of post-combustion CO_2 capture and increase the share of renewable energy. Several investigations have investigated the implementation of captured CO_2 in biorefineries for biofuel production as well as the transformation of the emitted CO_2 to valuable materials and chemicals.

Although the PC route has a positive impact on climate change, the overall performance is still not satisfactory. This, owing to the recycling process, has a negative impact on human toxicity, freshwater eutrophication and ozone depletion potentials because of the generation of secondary waste streams and the extra fossil fuels utilized in the recycling processes. Life-cycle assessment (LCA) is a common methodology that explores the various environmental impacts of targeted technologies. It also has the advantages of comparing potential scenarios regarding to environmental effects [192]. Although, there are environmental and economic assessments of a wide range of CO_2 capture processes. However, there is a research gap in this area related to the environmental impact assessment of carbon recycling.

The reutilization of emitted carbon dioxide from post-combustion carbon capture and utilization techniques contributes to the achievement of the circular economy. The main challenge here is that some PC carbon capture technologies still may not be economically profitable. To overcome this challenge, sustainable strategies could be adopted by developing technologies, marketing, increasing carbon taxes development of products and industrial processes and accessing emission reduction benefits. Figure 9 summarizes the main parameters in the carbon circular economy. Still, the chemical absorption of CO_2 is the most preferable technique for PC carbon capture technologies followed by membrane separation and adsorption processes. As mentioned before, the three main processes are suitable for post-combustion CO_2 capturing. There are different routes are used to attain carbon circular economy such as [193]:

- Mineralization: it refers to the reaction of alkaline earth oxides –based materials (such as MgO and CaO) with of CO_2, yielding valuable carbonate-based products can be developed from industrial wastes;
- Another route for this strategy is the biofixation where CO_2 is fixed by microalgae yielding numerous biological organic products, chemicals and biofuels via biorefining technologies. The biofixation has several merits such as the production of lipids, which the main feedstock for the production of green monomers, such as ethylene, as well as it can be transformed into bioethanol via some commercial reaction routes. The process needs large volumes of water, light intensity and land as well as the main nutrients such as carbon, nitrogen and phosphorus at specific concentrations and controlled pH and temperature (<45 °C). Additionally, purification of the flue gas stream from SOx, NOx, and heavy metals is essential to protect the microalgae. Future studies should focus on developing of the biorefineries, i.e., lowering the required area, conserve energy, improving the cell growth, the impact of the flue gas composition and load on the yield of the biomass and reducing the overall cost. Investigating the integration of renewable energy in these biorefineries is preferable;
- The third route is the adsorption of CO_2 onto efficient sorbents which are useful for high-pressure applications if the capacities and rates of these sorbents are being enhanced;
- Other routes for the post-combustion CO_2 capture such as cryogenic separation are investigated, however, this is process is not economic from circular economy view owning to its high energy demand.

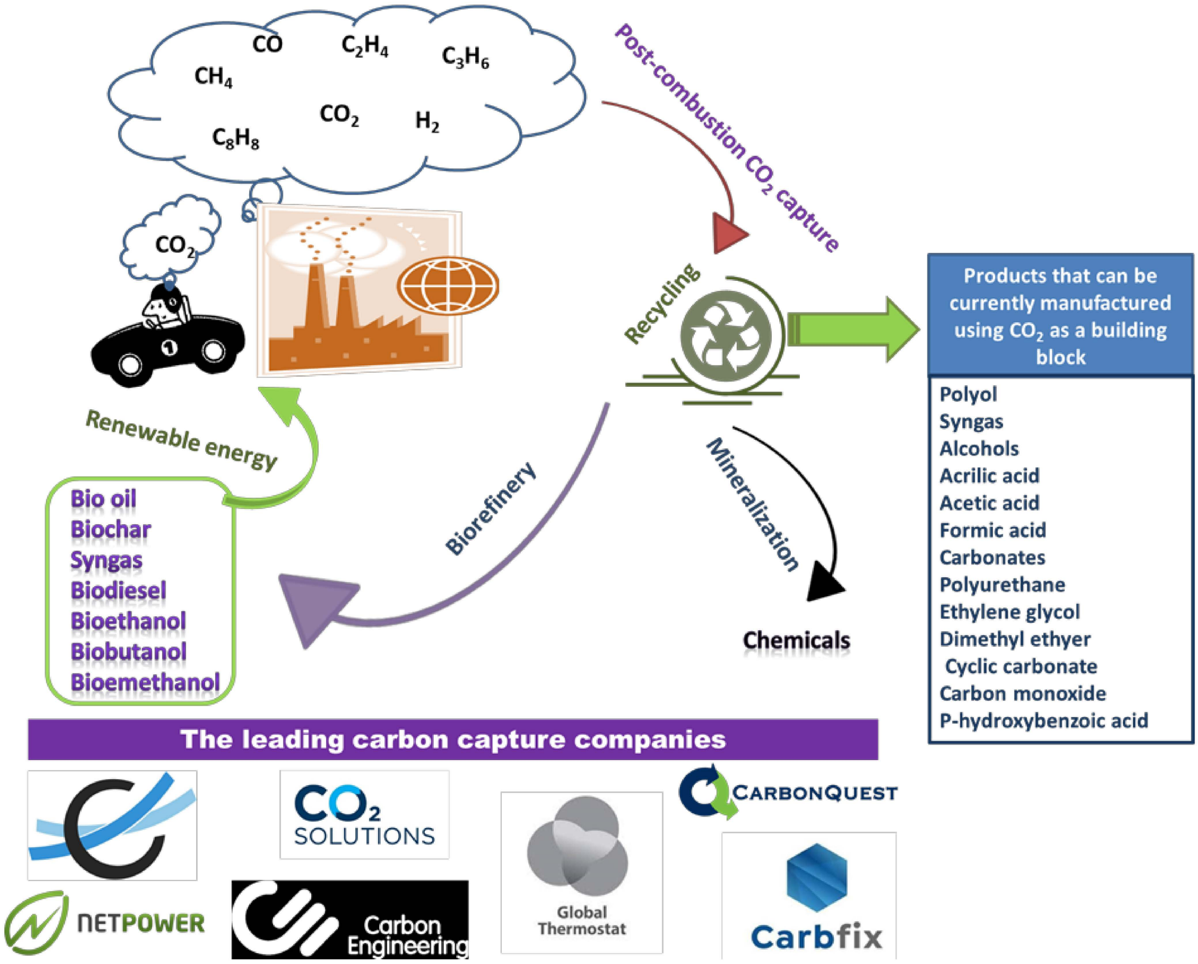


Figure 9. Schematic representation optimization of carbon circular and the leading companies in this area.

Catalyzed chemical absorption is a new technology which is based mainly on enzyme carbonic anhydrase. In this route, CO_2 is transformed directly to bicarbonate at high rates, slightly reducing the heat of desorption. Although the overall efficiency of this hybrid technique is high, the sensitivity to contaminants and temperature variation affects the lifetime of the enzyme. Hence, more research is needed to improve the activity and stability of the enzyme on the long run.

The main processes involved in the transformation of CO_2 into valuable products are polymer synthesis, CO_2 hydrogenation, electrochemistry, photo-electrochemistry, dry reforming of methane and oxidative dehydrogenation of light alkanes to alkenes. These main processes have some limitations. For example, the endothermic nature of the hydrogenation reaction yields low conversions at lower temperatures. Hence, future work should focus on optimization of these processes to increase their productivity. However, the carbon circular economy can give the recycling process the strength to expand towards new or modified value chains such as the production of secondary feedstock as well as valorization of other wastes developed during the material recycling [192].

A business model based on the integration of renewable energy and carbon capture and utilization in power2methanol plants was economically assessed. The proposal showed that this integration introduced a promising solution in the energy market [194]. Another study investigates the introduction of CO_2 in the manufacturing of polymers and co-polymers. However, such technologies are under development and it could be implemented in the processing of plastic wastes in different area around the world [195]. An environmental impact assessment of 27 studies based on carbon capture storage, carbon capture utilization and carbon capture and utilization has been reported. The results showed that the global warming reduction potential of CCU is much higher than CCUS and CCS. As well as the negative impacts of CCUS and CCS on the environmental (eutrophication, acidification, and toxicity potential) are much greater than that of CCU technologies [196].

The economic and ecological assessment of onshore- and offshore- CCS and CCUS-enhanced coal bed methane plants showed that the success of such projects is significantly attributed to the experience of targeted countries in this area, in addition to other challenges such as high cost of investment, renewable energy competition, implementation time on the long run [197]. Another study stated that the successful deployment of carbon capture utilization and storage with enhanced gas or oil recovery is depends on governmental support, in addition to the enhancement of CO_2 storage [198]. The valuation of CCUS reported that such projects still have low competitiveness in the energy market even with the governmental support and the considerable pace of development [1]. Transition from liner to circular economy yields development of the carbon utilization technologies as illustrated in Figure 10. In the past, companies were focused in the reduction in carbon tax expenditures rather than on CO_2 utilization [199].

There is a considerable interest in cost-effective processing of CO_2 which may be attributed to that CO_2 forms a precursor for new products or even current one. Hence, it already contributes in the existence markets and the potential to enter new markets is a key parameter that controls the interest of the investors in CCU technologies. Subsequently, improvement of current or new CO_2 utilization technologies will increase the number and deployment rate of these projects which has a positive impact in the context of circular economy and sustainable development [200]. The consumption of CO_2 in sequestration projects has been increased from 1.2 Mt in 1972 to 432.9 Mt in 2018 in carbon capture utilization and storage projects, from 1 Mt in 1996 to 68.7 Mt in 2018 carbon capture and storage and from 0.1 Mt in 1991 to 75.6 Mt in 2018 in carbon capture and utilization projects [201]. There is a main challenge for investigations and case studies related to this topic owning to the lack of database for such CO_2 sequestration projects. Despite this, we believe that this review could be helpful for investigations related to this area as a base for further discussion on the significance of carbon circular economy.

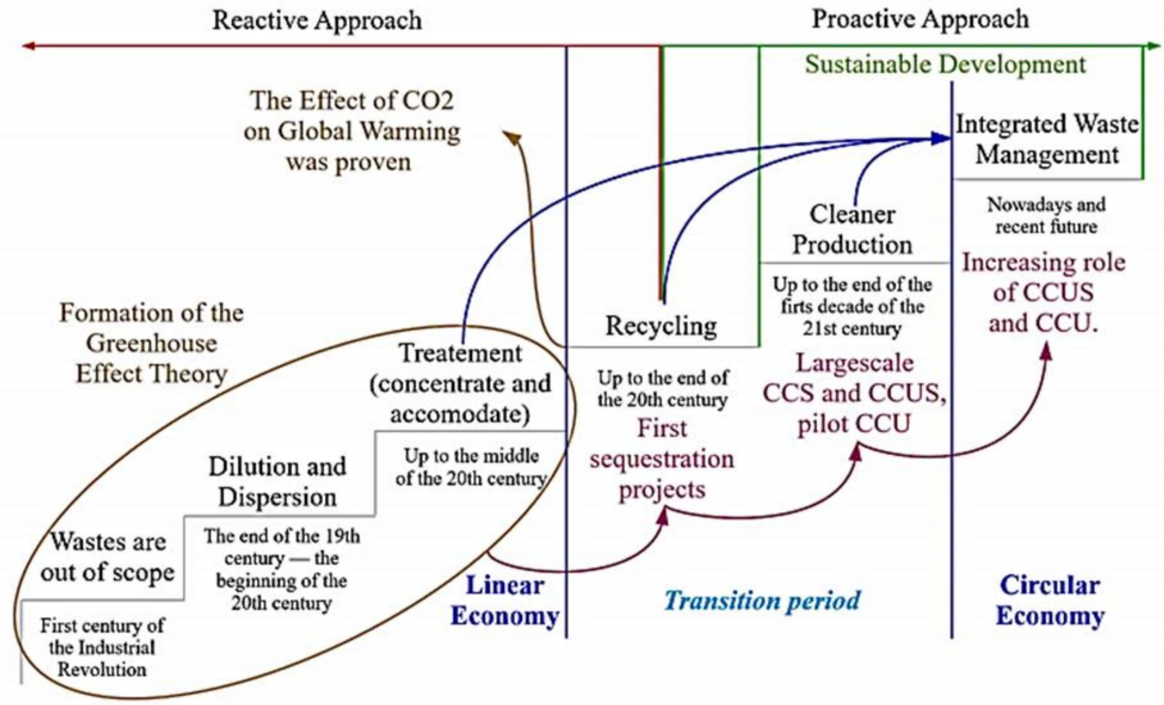


Figure 10. The impact of carbon sequestration projects on the transition from linear to circular [201], open access.

6. Prospects of Post Combustion Carbon Capture Technology

There are many research activities being conducted in the search for good sorbents for capturing carbon dioxide. Ammonia which is considered as a novel liquid sorbent has low energy consumption compared to monoethanolamine (MEA). An investigation conducted shows that 5 wt% ammonia applications in carbon dioxide absorption has the same consumption of energy as 30 wt% monoethanolamine functioning at lower temperatures [202]. Some factors are considered in the selection of ammonia as a suitable solvent absorbent includes ammonium salt precipitate as well as the solvent being volatile. A number of projects in recent times have utilized chilled ammonia in capturing of CO_2 [203–205]. There are other types of amines also investigated in other to enhance their carbon dioxide absorption capacity during monoethanolamine absorption. Methyldiethanolamine (MDEA) which is considered a secondary amine-based solvent has been investigated by several researchers around the world. This is simply because they tend to have higher carbon dioxide absorption capacity, higher stability thermally, low alkalinity, low volatility, low consumption of energy as well as not being susceptible to corrosion [206,207]. Despite all these advantages, MDEA has some limitations as well. They have slow absorption rate [207,208]. The addition of piperazine which is an activator caused the carbon dioxide absorption performance of the amine-based solvent to increase. Through research activities, there have been improvements in terms of thermal and oxidative degradation of MDEA [209]. The application of different blenders improved the performance of the amine based liquid sorbent. Blending MDEA and triethylene tetramine improve CO_2 absorption capacity of the MDEA [180,210]. Moreover, a blend between 2–amino–2–methyl–1–propanol and MDEA enhanced CO_2 capture as well as absorption rate of the MDEA [211]. Other research activities have also been conducted using ionic liquids as solvent sorbents. They usually come in a liquid state below temperature of 100 °C [177]. They also referred to as organic salt [183]. Selection of varied combination pair of the anion and cation changes their properties. Some advantages of ionic liquids for the capturing of carbon dioxide include wide liquid range, thermal stability, vapour pressure can be neglected, high carbon dioxide solubility and physiochemical characteristics being tuneable [212]. The major setback is the high viscosity of liquid solvent [213]. Table 5 shows some research activities being conducted using liquid sorbents.

A techno-economic analysis of where amine-functionalized solid sorbent (e.g., SiO_2/0.37 EB-PEI) in four configurations (fluidized bed (FLB), moving bed (MB), fixed bed (FB), and rapid thermal swing (RTS)) based on mathematical modeling has utilized in post-combustion CO_2 capture combined with internal heat integration has been investigated. The CO_2 capture cost of the four solid sorbent-based processes was approximately 48.1–75.2 \$/tCO_2, with a sensible heat recovery ranged from 45% to 58%. The CO_2 capture cost is lower than that of amine-based absorption unit which is equivalent to 62.8 \$/t-CO_2. This is attributed to the combined effect of internal heat integration and improved CO_2 cyclic capacity which suggest the feasibility of this 4 solid sorbent-based processes for post-combustion CO_2 capture. The technical performance was evaluated based on costs of electricity, CO_2 avoidance and CO_2 capture. The CO_2 capture costs of RTS, FB, MB, and FLB were 52.1, 48.1, 51.8, and 75.2 \$/tCO_2, respectively. The RTS, FB, and MB recorded CO_2 capture cost lower than that of MEA 30 wt% (62.8 \$/tCO_2) and higher than that of water-lean solvent (46.6 \$/tCO_2). Concerning the energy performance, the system was much better than that of the current CO2 capture processes [214]. A model "Aspen Plus" was used to stimulate and optimize the CO_2 (148.25 Nm^3/h) capture from air using MEA absorption to generate methane. A sensitivity analysis has been conducted to investigate the technical performance of the overall process based on capture rate, CO_2 loading of rich and lean absorption liquids, reboiler temperature, the consumed energy consumption and overall cost. At higher capture rates, the needed energy per ton of captured CO_2 increases due to a higher steam stripping rate, needed in the desorber, and at lower capture rates, the size of equipment (blowers and absorber) increases owning to the significantly larger volume of air applied. An electrical energy of 1.4 MWh/tCO_2 were obtained and a reboiler duty of

10.7 GJ/tCO_2. For the MEA base scenario, the capital cost increased by around 60% yielding CO_2 capture costs of 1691 \$/tCO_2. Based on the techno-economic evaluation, the calculated cost lowered to 676 \$/tCO_2. The overall cost varied from 273 to 1227 \$/tCO_2 based on varied economic factors such as heat price (2–\$20 \$/GJ), electricity (20–200 \$/MWh) and capital expenditure (±30%), and plant life (15–25 years) [215].

Table 5. Merits and demerits of liquid sorbents.

Type of Solvent	Sorbents	Merit	Challenges	Ref.
Amine based solvent	Ammonia	• Formation of salt with carbon dioxide ideal for the fertilizer industry. • There is the possibility of the energy consumption being reduced.	• Ammonia salt precipitating. • Solvent volatility	[216,217]
	Monoethanolamine	• Process efficiency is high • The rate of reaction with CO_2 is also high.	• Energy incentive • Volatility being high as well as corrosion	[218,219]
	Methyldiethanolamine	• Low volatility • Thermal stability • Less alkalinity • High carbon dioxide load • The cost of regeneration is also low	• Rate of reaction is slow	[207,220,221]
Amine mixture	Monoethanolamine + 2–Amino–2–methyl–1–propanol	• It performs better in terms of absorption capacity compared to Monoethanolamine • Combining with monoethanolamine produced a final product that has the characteristics of both	• Reduced absorption capacity • Efficiency is less than Monoethanolamine	[211,222]
	Methyldiethanolamine + Piperazine	• Higher stability compared to Monoethanolamine. • The presence of the piperazine helps reduce the possibility of thermal break down of the Methyldiethanolamine. • The final product also has lesser heat of absorption compared to Monoethanolamine.	• Piperazine activities reduced with temperature	[209,223]

Table 5. *Cont.*

Type of Solvent	Sorbents	Merit	Challenges	Ref.
Ionic liquid	Conventional ILs	• High CO_2 selectivity • Consume less energy than traditional solvents	• High viscosity	[224]
	Functionalized ionic liquids	• Improvement in the CO_2 absorption compared to normal ionic liquids. • They also have low surface tension compared to aqueous amine solution. • High storage capacity owning to the presence of functionalized group in their surfaces	• Viscosity is high compared to ionic liquids. • Performance reduces after regeneration • Complicated synthesis processes	[212,224,225]
	IL-alkanolamine-water mixture	• Higher CO_2 dissolution and Lower viscosities than conventional ILs	• Higher negative impacts on the environment than conventional ILs • Loss in amine are higher than conventional ILs • Consume less energy than amine but higher than conventional ILs	[224]
	Amine based ionic liquid + Methyldiethanolamine	• Presence of ionic liquid supports carbon dioxide absorption on the Methyldiethanolamine solution • The regeneration efficiency is high.	• Stability of sorbent is unknown	[226,227]

The use of carbonaceous materials for capturing CO_2 is also on the increase with several research activities also being performed in this area. For activated carbons, their surfaces chemistry is defined by heteroatoms and also managed by the characteristics of the raw precursors [228]. Today there are several groups of activated carbon being used in CO_2 capture because of technological advancement. Nano materials as explained earlier have high carbon dioxide capture capacities and sustainable in in multiple sorption and desorption cycles. The energy requirement for some of these materials is relatively low. The major limitations for this approach are that the process is expensive and is quite complicated. Controlling the size and dimension of these materials implies that specific materials will be needed to meet the required dimension. Subsequently, increasing the cost of the process is a result of the very complicated methodology involved. Screening and selection of ideal nanomaterial is also an issue but more research investigation must be geared towards developing cheap production route for these nanomaterials.

7. Conclusions

As the world continues to strive for the most effective approach in reducing toxic emissions, there has been a sudden rise in the different materials being used as sorbents for PC carbon capture technique. This investigation explored some of these materials and considered current and future research activities being performed in order to enhance their absorption capacity. The use of nano materials in spite of their high potential in carbon dioxide capture, area of their surfaces and adjustable characteristics still have some limitations in terms of market price for production as well as complexity. These two major limitations create a future research direction that must be critically explored to improve the commercialization of the technology.

Other capturing materials discussed in this investigation include activated carbons which is a carbonaceous material with high benefits when utilized in PC capture of CO_2. They have high stability, simple to manufacture and the manufacturing cost is cheap compared to others. The major limitations in the application of activated carbon for CO_2 capture are their stability, regeneration abilities, kinetics analysis, energy input, and environmental impacts. These limitations related to activated carbon also create a clear cut research direction that must be considered in the future investigations. Surface chemistry for carbonaceous materials is also important area that requires intensified investigation.

Using aqueous ammonia for capturing carbon dioxide is also another area that was discussed in this investigation. There is the urgent need for a novel reactor as well as additive development to enhance the absorption process. Pressure, temperature and the ammonia and carbon dioxide characteristics are some key parameters that define the CO_2 capturing process but the configuration of the reactor will also actively determine the mass transport characteristics between the liquid and the gas. Optimization of reaction conditions is also important as they determine the cost of the entire capturing process using ammonia. Future research must consider optimization of the entire reaction process that will yield the best results. A number of research activities carried out relating to ammonia are performed in micro field. There is the urgent need for micro reaction kinetics to be explored. A thorough investigation to reduce ammonia loses due to its volatility will improve the entire capturing process. A pragmatic way of reducing these loses is to apply low ammonia concentrations at lower reaction temperatures.

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