Review Article

Novel Systems and Membrane Technologies for Carbon Capture

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Due to the global menace caused by carbon emissions from environmental, anthropogenic, and industrial processes, it has become expedient to consider the use of systems, with high trapping potentials for these carbon-based compounds. Several prior studies have considered the use of amines, activated carbon, and other solid adsorbents. Advances in carbon capture research have led to the use of ionic liquids, enzyme-based systems, microbial filters, membranes, and metal-organic frameworks in capturing CO₂. Therefore, it is common knowledge that some of these systems have their lapses, which then informs the need to prioritize and optimize their synthetic routes for optimum efficiency. Some authors have also argued about the need to consider the use of hybrid systems, which offer several characteristics that in turn give synergistic effects/properties that are better compared to those of the individual components that make up the composites. For instance, some membranes are hydrophobic in nature, which makes them unsuitable for carbon capture operations; hence, it is necessary to consider modifying properties such as thermal stability, chemical stability, permeability, nature of the raw/starting material, thickness, durability, and surface area which can enhance the performance of these systems. In this review, previous and recent advances in carbon capture systems and sequestration technologies are discussed, while some recommendations and future prospects in innovative technologies are also highlighted.

1. Introduction

The continuous increase in gaseous emissions is a major environmental challenge that bedevils our planet as well as the global populace. Climate change and global warming are resultant effects of the release of CO₂, CH₄, chlorofluorocarbons (CFCs), O₃, and NOx into the atmosphere [1, 2]. The greenhouse gas contributions of chlorofluorocarbons/methane are far higher than those of CO₂ when compared on the basis of unit mass [2]. However, due to the release of CO₂ from fossil fuels, which is the primary source (98%) of the global energy demand, most of the efforts to combat the menace of greenhouse gases are concentrated on CO₂ capture technologies [3]. In the year 2013, the high greenhouse gas concentrations in the earth’s atmosphere were quite alarming; also, the CO₂ concentration was 396 ppm (i.e., about 142% of the estimated CO₂ concentration in the preindustrial era [4]. Findings from the Global Atmosphere Watch (a greenhouse gas bulletin) showed that CO₂ concentration experienced the highest increase between 2012 and 2013, compared to those reported for previous years. However, this was judged to have been caused by the reduction in CO₂ uptake in the biosphere. From 2013 to date, the increase in greenhouse gas emissions caused by a rapid rise in population density, industrial activities, and anthropogenic activities has given rise to unprecedented repercussions/effects ranging from environmental pollution to health deterioration, water contamination/pollution, ecosystem destruction, loss of aquatic life, and undesirable climate change. At a climate conference held in Paris (i.e., the COP21) in December 2015, a total of 195 countries instituted a resolution on the first-ever-historic legal-binding agreement on climate issues, where it was commonly agreed that the global temperature would be kept at an average increase of less than 2°C, which is slightly above what was obtainable in preindustrial times.
The resultant rise in the world’s fossil fuel reserves alongside the rapid change in energy demands has led to the unavoidable global expansion of some existing plants, as well as the construction of new ones in order to boost production capacities as a preparatory measure to absorb the global energy shocks. This situation has extended into further years owing to the current state of industrial development and economic growth in different parts of the world, especially in the developed nations. According to the information provided by the Energy Information Administration (EIA), an arm of the US Department for Energy, while fossil fuels were projected to be the world’s leading source of energy (80% of the world’s energy) in the next two decades, energy consumption was predicted to also rise by 56% by 2040.

According to the literature, the CO₂ emissions from power plants were predicted to rise by 46% in 2010 [5]. Furthermore, according to EIA reports, the combined CO₂ emissions from India and China from the use of coal are expected to triple that of the US by the year 2030 [6].

Three strategies are employed in trapping CO₂ emissions from fossil fuel-powered plants; the methods include oxy-, pre-, and post-combustion capture of CO₂ [7]. In pre-combustion capture, the gas is trapped from the parent mixture prior to undergoing combustion. Oxy-combustion capture has to do with capturing CO₂ during combustion, i.e., while burning gas in the air. In postcombustion capture, the gas is trapped from flue gas (a mixture of constituents such as nitrogen, water vapor, and oxygen), in a downstream unit retrofitted with a carbon capture system within the plant. The challenges associated with this process include low CO₂ partial pressure, high flue gas temperature, and the high amount of CO₂ in the flue gas [7, 8]. This also confirms why coal-fired power plants have been reported to be one of the largest stationary point sources of CO₂ emissions [9].

In the United States, policy implementation for CO₂ reduction exists at the local and state levels [10]. However, requests to build new coal-fired power plants are being denied regularly due to their lack of CO₂ controls at inception as well as their medium to high tolerance for CO₂ emission [11]. In 2009, 44.5% of US electricity was generated from coal, whereas, in 2008, CO₂ emissions from electricity generation accounted for about 40 and 34% of the global anthropogenic and GHG emissions [12, 13]. Globally, 31.2 Gt CO₂ emissions were told to have been released from fossil fuel combustion and cement production [14]; this value dropped by 1.3% in 2009 [15].

1.1. Some Related Reviews on Carbon Capture. In the study of Leung et al. [16], various aspects of carbon capture systems and some current state-of-the-art technologies for CO₂ capture, transport, separation, storage, leakage phenomena, monitoring, and life cycle analysis were discussed. They asserted that the choice of a specific CO₂ capture technology depends on the nature of the CO₂-generating plant and fuel source. Based on their discussions, absorption is the most preferred method for capturing CO₂ and according to them, it is due to the higher efficiency and cost-effectiveness of the process. Vakharia et al. [17] scaled up the performances of synthetic amine-doped thin-film composite membranes for CO₂ capture from flue gas, where they recorded CO₂ permeance > 700 GPU (1 GPU = 10⁻⁶ cm³ (STP)/(s cm² cmHg)) with corresponding CO₂ selectivity above 140 at 330 K. Aaron et al. [18] carried out a review of some existing CO₂ capture technologies; they concluded that the most viable method for CO₂ capture is absorption using MEA. Other liquid absorbents, i.e., piperazine and anionic liquids, have also been discussed as potential candidates for carbon capture [19]. However, piperazine which flows and reacts faster with CO₂ than MEA has been proposed owing to its larger volatility relative to MEA; hence, its usefulness in CO₂ absorption is quite expensive and which is the reason for its noncommercialization [20]. The review conducted by Brunetti et al. [21] compares CO₂ separation involving membranes and other separation technologies, i.e., adsorption and cryogenic separation of CO₂. They highlighted that membranes are strongly affected by low CO₂ concentration and pressure from flue gas, which is a major hurdle in applying this technology.

Chemical absorption or scrubbing process is currently the technology most likely to be implemented in the near future but is rather energy-intensive. In recent years, membrane-based CO₂ separation appears to be a competitive substitution for conventional chemical absorption technologies. Wang et al. [22] reviewed the basic process design techniques for some CO₂ absorption processes using chemical solvents and membranes; they also highlighted the need to optimize some operational parameters, techniques for process modification, membrane module types, etc., in which the energy requirements and economic implications of both CO₂ capture technologies were scrutinized. However, they asserted that membrane-based separation lacks obvious advantages, in terms of energy requirement and cost, over MEA-based absorption where 90% CO₂ capture is feasible.

Based on the review carried out on carbon capture and utilization (CCU) by Koytsoumpa et al. [23], commercial applications of the thermal power and industrial sectors of pre- and postcombustion captured carbon were discussed. The focus of CCU is for the trapped CO₂ to serve as fuel or as a means of generating heat and power. Hence, they asserted that CCU combined with energy storage is an evolutionary approach for instilling the power to fuel concept, which in turn guarantees high market supplies of fuel and other chemicals. Furthermore, recent advances in supercritical CO₂ cycles for heat and power production were also presented.

Owing to the different types of absorption, adsorption, membrane, and cryogenic processes available for carbon capture operations, absorption still stands out as the most widely used method in commercial applications. Based on the content and composition of treated gas samples, different physical and chemical methods of adsorption are available for carbon dioxide and sulfur species removal from process streams [24–27]. For mixtures containing low amounts of carbon dioxide, chemical solvents are preferred to physical solvents; however, physical solvents give better results at high partial pressures. In addition, the thermal energy
requirement for gas separation processes involving chemical solvents is much higher compared to those of physical solvents due to the addition of heat via the reboiler attached to the stripper column [25]. This is because, according to Henry’s law, the loading capacities of physical solvents have a virtual linear relationship with the partial pressures of the components to be removed, which in turn allows for easy solvent regeneration by pressure throttling. The dissolution of carbon dioxide in the physical liquid solvent is attributed to the van der Waals or electrostatic interaction and is optimal at high pressure and low temperature, hence the need to optimize the process conditions for optimum CO₂ capture.

A review of the development of novel carbon capture technologies was conducted by Lockwood [28], where their energy requirements and cost implications were compared in terms of efficiency-penalty, cost of power, cost of the CO₂ capture process, and the current developmental status of new technologies. For operations that actually factor in the cost of CO₂ capture into the power generation process, chemical loop combustion or the oxyfuel-based Allam cycle offers great potentials to meet the economic requirements of the overall process. For retrofit designs, high performance is often associated with CO₂ capture. According to them, in the US, the post-, pre-, and oxyfuel combustion research programmes present some ambitious targets for new technologies to achieve a CO₂ capture cost of about $20 per tonne. Novel solvents are seen to tilt towards lower-cost involvements in terms of energy regeneration requirements as compared to those associated with conventional amine solvents, phase-change systems, ionic liquids, other non-aqueous solvents, and enzyme-activation systems which are all promising technologies. Alternatively, other commercial gas separation technologies involving solid sorbents, membranes, and cryogenic separation have also been widely investigated. Although there are obvious cost implications for postcombustion capture applications, these techniques may offer some measurable benefits to precombustion capture systems, especially in areas where higher CO₂ partial pressures are desired. Hence, the integration of the CO₂ capture step and the water gas-shift reaction occurs within the adsorbents or membranes. In oxyfuel combustion, pressurised systems have shown a high tendency for efficiency improvements within the supercritical CO₂ cycle at some unique conditions of combustion. Ceramic membranes for oxygen production were also recommended as a means of lowering costs relative to those obtained for cryogenic air separation. Dramatic energy saving can also be achieved via chemical looping strategies, as a result of the inherent avoidance of the possibility of a gas separation step. This technology offers significant scale-up options to companies and research institutes, where the focus is on low-cost oxygen carriers. Raza et al. [29] reviewed the various processes involved in the reduction of CO₂ emissions where it was mentioned that carbon capture and storage techniques hold high promises for reducing the global carbon footprint. Their thought pattern focused on a CCS technology that deals with the capture and storage of CO₂ in deep geological formations for the regulation of the earth’s temperature.

Some basic guidelines/principles for long-term CO₂ sequestration and storage were also discussed with considerations for the processes and mechanisms (buoyancy, pressure gradient, reservoir heterogeneity, dispersion, diffusion, mineralization, phase trapping, and adsorption by organic materials) involved alongside the various interactions stimulated by supercritical CO₂ injection into the subsurface of geological sites. According to the authors, the selection of apt geological sites for CO₂ storage is informed by the physical characteristics of CO₂ and its phase change tendencies as influenced by CO₂ transport/hydraulic pressure and temperature variation. Although CO₂ can exist as liquid, solid, or gas, it often exists as a supercritical fluid at geological formations whose depths are greater than 800 m and this is as a result of an increase in pressure and temperature at such depth [30, 31]. According to the review conducted by Sood and Vyas [32], CO₂ can be trapped from process facilities and transported to sedimentary basins, saline aquifers, and coal reservoirs for storage. The basic techniques highlighted include oxy-, pre-, and postcombustion strategies. Based on the storage capacities of the CCS technique, it is obvious that the storage capacities of CCS systems make them the most prospective candidates for carbon capture and storage owing to the huge tons of CO₂ storage capacities of the aforementioned sites. However, issues that bother on safety are paramount, especially when these sites are overburdened by excessive pressures that may subsequently result in hazards.

Despite all the efforts put into the well-appreciated past reviews as highlighted in some of the documented literature, it is evident that none seems to have looked into the collection of research works that have dovetailed the application of hybrid systems/novel solvent systems in membrane technologies and the best potential candidates for carbon capture in lieu of the excellent properties they offer in those combinations. This then served as one of the major motivations for this study. Others include the scarcity of literature on the capture of several other carbonaceous compounds and the ill conceptualization of carbon capture in the light of CO₂ capture only.

To date, a lot of attention has been given to CO₂ capture due to its very high concentration in the earth’s atmosphere relative to other gases; this has also led to the minimal attention received by other greenhouse gases, hence another motivation for this research, which serves to advocate for the focus on hybrid technologies for the trapping of CO₂ and other carbonaceous substances rather than paying attention to CO₂ only. Also, researchers are still searching for better strategies for curbing the global carbon footprint by trying out new measures that are not only highly efficient but also cost-effective and environmentally friendly. This is because, while a lot of the existing techniques are targeted at CO₂ capture, a myriad of these techniques lack high CO₂/carbon selectivity, stability, durability, etc. Hence, this paper seeks to uncover some of the advances made in carbon capture research, as well as consider possible ways of improving on the current technologies, all aimed at optimizing their performances towards ensuring a clean environment. Although somewhat efficient, the known/aforementioned CO₂ capture
technologies are quite expensive, thus giving an estimate of about 70–80% of the overall cost of a full CCS system, capture, transport, and storage [33]. Therefore, significant R&D efforts are currently focused on the reduction of operating costs and energy penalties which must be borne out of strategic selection of the choice materials, such as hybrid technologies, without a compromise for low quality while optimizing the process conditions towards ensuring high carbon selectivity and separation. All of these alongside discourses on the use of modified hybrid systems/MOF-ionic liquid systems for multigas (CCl3, CCl4, CH4, H2Cl2, CFCs, etc.) capturing are barely available with major attention given to conventional absorption/adsorption processes alongside oxy, pre-, and postcombustion capture processes for CO2 sequestration because the term carbon capture is often seen to be limited to CO2/CH4 capture as evidenced by the available literature. Also, any carefree attitude in this regard/the neglect of other greenhouse gases will gradually result in the accumulation/build-up of these gases to the point that they begin to constitute serious problems.

1.2. Categories of Carbon Sequestration Technologies. The existing carbon capture technologies can be grouped into the following categories.

1.2.1. Physiochemical Absorption

(1) Physical Absorption: Selexol, Rectisol, Fluorinated Solvents, and Ionic Liquids. Physical absorption involves the reversible/nonreversible use of solvents that have high affinity for carbonaceous substances; these solvents include methanol, propylene carbonate, dimethyl ethers of polyethylene glycol, fluorinated solvents, and the most recent group known as ionic liquids. Ionic liquids (ILs) are liquid salts of cations and anions; they have boiling points of less than 100°C and have the ability to trap CO2 from a mixture of gases [34–36] owing to their inherent properties, such as low volatility, high CO2 solubility, thermal stability, and their susceptibility to structural tuning that allows for the attainment of certain advantageous properties [37–39]. Several studies involving ILs have been devoted to determining the extent of CO2 solubility, selectivity and IL performance, as well as their thermal/chemical stability [34, 40]. Some advances on the use of amine-modified ILs or task-specific ILs (TSILs) [41, 42] have shown that these liquids have high affinity for CO2. Although the literature has recorded some significant advances in the production of low-viscosity ILs, one common challenge associated with the use of TSILs/ILs is the high viscosity of the fluids after CO2 entrainment during gas separation processes. Another solvent trapping process for CO2 capture is the Rectisol process. The Rectisol process (Figure 1) uses cold methanol to trap acid gases such as CO2 from contaminated gas streams [43–45]. The Fluor process employs propylene carbonate (C3H6O3) and CO2 partial pressure for removing CO2, while the Selexol process makes use of dimethyl ethers of polyethylene glycol in trapping CO2 at pressures ranging from 2.07 to 13.8 MPa.

The use of Purisol, Rectisol, Selexol, etc., is common in the oil and gas industry, and they are often preferred over chemical solvents at high acid gas partial pressures. Choosing the right solvent for natural gas sweetening seriously depends on factors such as gas composition, temperature, and partial pressure of gas, as well as the product specs. The works of Tennyson and Schaaf [46] and Kohl and Nielsen [45] are recommended for due consultation by readers. Over a wide range of conditions, aqueous amines are suitable for acid gas absorption from natural gas; however, these solvents still have some serious shortcomings, which include high energy costs for solvent regeneration [47], low CO2/H2S selectivity, corrosivity, and high volatility. This, however, sparked off the need for other viable alternatives which in turn ushered in the era of ionic liquids. Considering the past few decades, a huge chunk of studies have discussed the solubility of CO2 relative to other acid gases in several ionic liquids [34, 48]. However, evidence has shown that, for high gas absorptivity of CO2 in ILs, CO2 solubility is trivial relative to the selectivity because the latter gives more credence to the degree of separation obtained from an absorption process [48]. In clear terms, considering the opinions of experts, despite the essentiality of both parameters, CO2 selectivity is more dependable relative to its influence on the absorptivity of ILs. In another study, CO2 absorption-desorption rates in polyionic liquids (hybrid system) were reported to be much faster compared to those of ionic liquids and the processes are totally reversible [49–51]. The absorptive potentials of ionic liquids, monomeric and polymeric materials, rely on the chemical and molecular structure of the ions/anions that make up the polar ends of the liquids [50]. Generally, ILs are characterized by low vapor pressures, nonflammability, chemical/thermal stability, tunable polarity, reliable electrolytic properties, and easy recycling [52].

A method to determine the bubble-point pressures of CO2 and CH4 at temperatures of 303.15 and 363.15 K and at pressures up to 14 MPa using the Peng–Robinson Equation of state and the van der Waal’s mixing rule, in ionic liquids, was established by Ramdin et al. [53]. The solubility of CH4 was estimated to be 10 times lower than that of CO2 on a mole fraction basis. Furthermore, Henry’s constants for CO2 and CH4 for all the ionic liquids (ILs) were used to determine the ideal CO2/CH4 selectivities which gave values comparable to those obtained for the Selexol, Purisol, Rectisol, Fluor, and sulfonate solvents. The estimated CO2/CH4 selectivity decreased at increased temperature and molecular weight. Genduso and Pinnau [54] also carried out a study that deals with the estimation of the sorption, diffusion, and plasticization properties of cellulose triacetate polymer films in a mixed-gas (CO2/CH4) environment.

(2) Chemical Absorption: Methanol Amine (MEA), Caustic Alkali, and NH3. The Warrior Run coal-fired power station in the United States has a CO2 capture capacity of about 150 t/d. Amongst the choice solvents for CO2 capture, MEA is the most widely used amine amongst other members of...
the amine family because the CO₂ recovery rate and product purity are as high as 98% and 99%, respectively. However, one major demerit of this method is the tendency for MEA degradation when it is in contact with the oxidising environment of flue gas, whereas the energy requirement for the regeneration of the spent solvents can reduce energy costs by about 40% when compared with the cost incurred from using conventional MEA solvents. Hence, alternative solvents such as sterically hindered amines have been proven to possess good absorption and desorption features with minimal degradation or low solvent loss during carbon sequestration [27].

Till date, the most widely adopted technique for CO₂ capture from postcombustion processes/flue gas involves the use of aqueous solvents such as (MEA), diethanolamine (DEA), and methyl diethanolamine (MDEA) as well as hybrid systems which comprise of a mixture of more than one amine [55–57] or blends of amines and chemical solvents such as Ca(OH)₂ (Figure 2). Gas scrubbing, using alkanol amines, is one of the most widely adopted cost-effective strategies available on commercial scale for post-combustion CO₂ capture [58].

In order to overcome the limitations posed by amine-based solvents for stripping CO₂ from flue gas, they can (i) be doped with 0.1 M Ca(OH)₂ + 27.3–30% DEA at pressures of 2–2.7 bar for optimum CO₂ capture of about 98.3–99.6% (Figure 3) or (ii) be replaced with aqueous ammonia for CO₂ separation owing to its inherent lower heat of absorption. In addition, liquid ammonia (NH₄OH) is known to be able to trap impurities such as NO and SOx that are present in the gas stream. However, one major setback associated with the use of ammonia-based solvents is the recurring need of lowering the flue gas temperature prior to it being introduced in to the absorption column; this helps to abate the ammonia losses that would have ensued if the flue gas was introduced into the absorption column at higher temperature. High gas temperature increases the energy requirement of a large volume of flue gas that is yet to be treated [59]. Another limitation associated with the use of liquified ammonia for CO₂ capture is that the chilled ammonia may foul heat exchangers as a result of the deposition of ammonium bicarbonate from saturated liquids [7].

1.2.2. Cryogenic Separation. Cryogenic separation of CO₂ from a gaseous mixture is done via simultaneous cooling and condensation. Cryogenic separation is commercially adopted for streams with >90% CO₂ concentrations; however, the process is not economical for more dilute CO₂ streams. One major limitation of cryogenic separation of CO₂ is the amount of energy required to enforce refrigeration, especially for dilute streams. Also, dehydration of the gaseous stream is a necessary step prior to cooling because it helps to prevent plugging/blockages. In lieu of the aforementioned limitations, cryogenic separation of CO₂ engenders the production of liquid CO₂ as a transport fuel for ships [60]. Cryogenic operations are often compatible with highly pressured/concentrated gaseous mixtures, such as in precombustion or oxygen-fired combustion processes.

To date, cryogenic sequestration of CO₂ is deemed unrealistic owing to the high cooling costs incurred from the process; hence, there is a need for new developments/methods for cutting down the huge costs associated with cooling the gas. The work of Knapik et al. [61] suggests that the cold duty for a CO₂ separation protocol must come from an integrated liquefied natural gas (LNG) regasification or cryogenic air separation system, which takes advantage of an attached CO₂ liquefaction and separation module that helps to ensure the efficient denitrification of natural gas towards ensuring low energy consumption. Natural gas denitrification is a subject that is poorly addressed by the current body of literature; this then flags the extent of the urgency of research works that qualitatively address the subject matter. According to Knapik et al.
the cryogenic separation of CO₂ considers the separation of liquid CO₂ from flue gas generated from oxy-fuel combustion. The outlet N₂ stream transiting from an N₂ removal unit (NRU) serves as the cold stream from the condenser that helps to liquefy CO₂. As a result of the low temperature generated from nitrogen expansion, the inclusion of an external refrigeration cycle is not required, and this makes the process somewhat economical. The amount of trapped CO₂ from the process is a function of the flue gas composition and operating pressure. Based on their findings, 83.07% CO₂ of 99.17% purity can be captured in this process. The energy required for separating the liquified CO₂ is 0.125 kWh/kg CO₂ or 449 kJ/kg CO₂. This novel CO₂ separation unit offers a unique opportunity to produce liquified CO₂ at moderate conditions; the integration of both cryogenic processes is technically and economically advantageous. Xu and Lin [62] successfully carried out the cryogenic separation of CO₂ from flue gas generated from natural gas. They asserted that the hybrid NRU-CO₂ capture installation is an innovative concept with good commercialization potential. The optimization of a cascaded thermodynamic system for separating CO₂ from liquified natural gas has been investigated [63], while the effect of multiple cryogenic desublimation on the dehydration and decarbonization of natural gas was studied by Ali et al. [64]. Song et al. [65] carried out a study that bothers on the cryogenic separation of CO₂ on Stirling coolers via heat integration.

1.2.3. Membrane Separation/Absorption. The performance of membranes for carbon capture processes is measured by the ease with which the component of interest adsorbs onto the surface of the membranes whilst allowing the permeation of other components. Membrane types include porous inorganic membranes, palladium-based, ceramic, polypropylene, polyphenylene oxide/polydimethylsiloxane (for gas separation), polymeric, zeolite, and MOF membranes, which cannot give high degrees of separation, and thus would require the integration of multiple stages and/or recycle streams. In lieu of this, problems such as process complications, energy consumption, and high costs often arise. Hence, solvent-assisted membranes are being developed to combine the best features of membranes and solvent scrubbing. Much development is required before membranes could be used on a large scale for carbon capture in power stations [44].

Polymeric membranes (Figure 4(a)) are classified as dense membranes which include polyimides, polysulfones, and cellulose acetate as well as their derivatives. Another group is one that comprises fixed-site carriers (FSC) (Figure 4(b)); they are made by coating polyvinyl amine on several supports. These membranes ensure high CO₂ selectivity and gas permeation/rejection by means of an integrated carrier within the membrane. The third group includes membranes fused with low-vapour-pressure liquids (e.g., K₂CO₃ or diethanolamine) as supports for housing the immobilized carrier within the membrane pores (Figure 4(c)). The three mechanisms (diffusion, sieving, and
solution diffusion) responsible for gas adsorption in polymeric membranes are as illustrated in Figure 5.

In the study carried out by Tan et al. [66], a flexible microporous organic polymer (MOP) tagged BOP-1 was synthesized and functionalized using Cl and NH$_2$ moieties. Their findings revealed higher CO$_2$ uptake within a pressure limit of 1 bar, thus giving CO$_2$-trapped concentrations of 3.94 and 1.60 mmol/g at 273 and 298 K, respectively. At 273 K, the polymer selectivity for CO$_2$/CH$_4$ was abrupt, i.e., 568 at 0.02 bar. Considering the experimental and theoretical validations, they asserted that the –CH$_2$–NH– linker within the polymer framework played a significant role in enhancing CO$_2$ polymer binding and was thus responsible for the flexibility of the entire framework. Amongst the diverse CO$_2$/CH$_4$ sequestration technologies, porous materials are very ideal candidates owing to their high energy efficiencies and low operating costs [67].

For MOFs, some major limitations in their use include the high energy requirement of the solvent regeneration process, thermal stability of the amine system during regeneration, and the presence of impurities that are present in the flue gas stream, which may have some significant effect on the chemical stability and sorption capacity/potential of the solvent [68, 69]. MOFs are a class of porous materials comprising of a network of metal ions/clusters of nodes connected by organic ligands; they have a wide application in gas separation processes [70, 71]. These materials have very high surface areas, ultrahigh porosity, and flexibility, which is imposed by the presence of ligands/connectors [70, 72–78]. One major merit of MOFs over other solid adsorbents lies in their adaptability to pore size tuning and framework functionalization, which are premeditated by carefully selecting suitable ligands, functionality/surface enhancers, metal ions, and the mode of activation. The limitations of MOFs are more pronounced in humid environments and this has led to a probe into understanding their mechanisms of operation during gas adsorption, which has further stimulated the development/integration of novel

**Figure 4:** Schematic view of (a) dense polymeric membrane, (b) fixed-site carrier membrane, and (c) supported liquid membranes (adapted from Bolland [44]).
structures, hybrid systems, and technologies as means of improving their adaptation to such environments. The strategies adopted in improving the performance of MOFs include the following.

(1) The Opening up of Metal Sites. This involves the removal of solvent molecules connected to metal nodes by the creation of a vacuum or application of heat after synthesizing the metal framework during chemical activation. The presence of open metal sites in MOFs impacts their CO₂ selectivity and the binding energy between adsorbed CO₂ molecules and the MOF surface. This helps to open metal centers/binding sites where CO₂ molecules can become attached and bind the pore surface via dipole-quadrupole interactions. A method that helps gain insight into the interactions between trapped CO₂ and the ionic force field generated by open metal sites in MOF-74 has been developed. The procedure adopted allows for the accurate estimation of the adsorption isotherms that enhance the subsequent evaluation of the hypothetical open metal sites in MOFs [79]; the findings corroborate the results of Kong et al. [80]. Some widely used MOFs include HKUST-1, M-MIL-100, M-MIL-101, and M-MOF-74, where M represents the metal site. In order to accurately determine the influence of open metal sites in MOFs, it is expedient to isolate the effects contributed by the organic ligand, the synthetic route, and the nature of the inherent functional groups present in the MOF framework. For M-MOF-74 subjected to low pressures, some authors have confirmed the suitability of light metal sites for its surface area enhancement alongside its CO₂ uptake [81]. An examination of the effect of metal centers in M-MOFs was done using a computational approach [81–83] that portrays Rh, Pd, Os, Ir, and Pt as ideal candidates for enhancing CO₂ capture within MOFs. Casey et al. [84] carried out an investigation on the adsorption mechanism and electrostatic force field created by metal centers comprising of Mo, Ni, Zn, Fe, Cu, and Cr in the isomers of HKUST-1. They observed that divalent metals such as Mg²⁺ helped to improve the binding potential of CO₂ which in turn enhanced CO₂ selectivity. It was also observed that the mode of activation of the metal matrix also influenced the MOF’s affinity for CO₂; their results also support the findings in the work of Llewellyn et al. [85], in which they confirmed the effect of different activation methods on CO₂ loading using MIL-100 and MIL-101. The interaction of CO₂ and unsaturated Cr(III), V(III), and Sc(III) metal sites in MIL-100 framework was studied using variable-temperature infrared spectroscopy. The estimated adsorption enthalpies for Cr(III), V(III), and Sc(III) were −63, −54, and −48 kJ/mol, respectively; these are the highest ever-recorded CO₂ adsorption enthalpies on MOFs with open metal centers [86]. The work of Sumboon et al. [87] involves the synthetic characterization of M-DABCO metal series (M = Ni, Co, Cu, and Zn), in which they systematically tested the effect of different metal centers on surface area, pore volume, and CO₂ uptake. They asserted that, of all the tested metals, Ni-DABCO possessed the highest pore volume and specific surface area as a result of the high charge density concentration at the metal center. A close comparison of the M-DABCO with MIL-100(Cr) and an activated carbon (AC) sample showed that the presence of the unsaturated cations gave CO₂ uptake of 180 cm³/g as compared to the values obtained for the Cr and AC samples which are 60 cm³/g and 30 cm³/g, respectively [88].

(2) Presynthetic Modification of Organic Ligands. Organic ligands/linkers are the functional bridges that help connect a network of metal nodes; hence, they are responsible for the final outlook of the framework structure, pore volume/pore window, and surface area, which are highly essential for the successful sequestration of CO₂. Ligand functionalization infuses some active functional groups into MOFs which

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**Figure 5: Mechanism of diffusion of gas through membrane pores (adapted from Bolland [44]).**
produced MOFs had surface areas of 63, 71, and 2.5 m²/g from 2-aminoterephthalate (ABDC), Mg, Co, and Sr. The et al. [92] synthesized three amino-functionalized MOFs caused by solvent removal from the MOF framework. Yang et al. [93] made use of 3-amino-1,2,4-triazole ligands in designing a 3D MOF structure of characteristic area, pore volume, and CO₂ uptake of 782 m²/g, 0.19 cm³/g, and 4.35 mmol/g, respectively, at 1.2 bar and 273 K. Furthermore, the estimated enthalpy of adsorption of the Mg-ABDC, which also corresponds to a high heat of adsorption [92]. Shimizu et al. [94] used 3-amino-1,2,4-triazole ligands to design a 3D MOF structure of characteristic area, pore volume, and CO₂ uptake of 782 m²/g, 0.19 cm³/g, and 4.35 mmol/g, respectively, at 1.2 bar and 273 K. Furthermore, the estimated enthalpy of adsorption of the Mg-ABDC was 40.8 kJ/mol at zero coverage, which is very close to the value (48.2 kJ/mol) obtained for a commercial zeolite (NaX) sample. Xiong et al. [94] employed nitrogen atoms and methyl functional groups supported on 5-methyl-1H-tetrazole ligands in synthesizing UTSA-49 framework. The synthesized MOF gave a CO₂ uptake and enthalpy of 13.6 wt.% at 1 bar, 298 K, and 27 kJ/mol, respectively. The results obtained from testing the effects of the triazolate ligands were found to be in close agreement with the findings of Gao et al. [95]. Hence, it becomes very pertinent to gain good insight into the mechanisms behind the synergistic effects offered by the pore-surface-imposed functional groups as well as their size exclusion effects owing to their potential in optimizing the performance of functionalized MOFs.

(3) Postsynthetic Functionalization of MOF-Metal Matrices. Postsynthetic functionalization of MOFs helps guide against the limitations imposed by presynthetic functionalization. However, an accurate control of the process conditions is required, which is aimed at retaining the service life and stabilities of the unstable functional groups during solvothermal synthesis. In addition, the infusion of other functional groups into the synthetic mix may result in the distortion of the metal framework as a result of the improper mixing and steric hindrance that occur during crystallization, thus yielding undesired products. The insertion of functional groups at metal sites at the presynthetic stage of the framework casting may adversely affect the building blocks of the MOF, which may in turn lead to the structural deformation of the crystal lattice of the MOF [96–98]; hence, postsynthetic functionalization is considered a viable approach for combatting the highlighted shortcomings towards capacitating the resulting MOFs for high carbon/CO₂ capture. Some amine-moiety-modified solid adsorbents [99–102] and MOFs [103, 104] have shown improved CO₂ sorption over their unmodified counterparts. Lee et al. [105] grafted 16.7 wt.% diamine into MOF-74/Mg(dopbdcc) at room temperature. The modified MOF exhibited a CO₂ uptake of 13.7 wt.% at 0.15 bar, while McDonald et al. [106] reported a CO₂ uptake of 12.1 wt.% for N, N'-dimethyl ethylenediamine grafted into Mg(dopbdcc). The isosteric enthalpy of adsorption of CO₂ ranged from 49 to 51 kJ/mol, thus confirming chemisorption of CO₂ molecules, whose kinetics was determined by the formation of carboxylic acid as identified using the Fourier transform infrared (FTIR) spectroscopy. The multicycle adsorption evaluation of the grafted Mg(dopbdcc) only revealed a 3% loss of CO₂ uptake after the 5th cycle; however, the MOF was found to be hydrologically stable with a high CO₂ uptake. The work of Chernikova et al. [107] bothers on the synthesis of a nanoporous fluorinated MOF named “SIFSIX-3-M,” where M = Zn, Cu, or Ni, which encompasses a periodic arrangement of fluoroine moieties in an enclosed one-dimensional (1D) channel; the synthesized MOF was seen to have a remarkable CO₂ selectivity over CH₄ and H₂ in several gas mixtures. Tables 1 and 2 consist of properties of some MOFs measured at high and low pressures, respectively. Comparing the results in both tables shows that higher selectivities are somewhat guaranteed at low pressures than at high pressures. The highest recorded selectivity was obtained for UTSA-49 in Table 2, with a selectivity of 95.8% at 1 bar and 298 K.

Since studies on the sequestration of other carbonaceous substances are rare in the literature, the three processes itemized in ”(1), (2), and (3)” can be tried for the different MOFs discussed in line with their capacities to trap CH₄, CHCl₃, CCl₄, and CH₂Cl₂, and their compatibilities with the substances.

Reports have it that polymers of intrinsic microporosity (PIM) are also prospective starting materials for the synthesis of ultrapermeable thin-film composite (TFC) membranes. This is because PIMs are known to provide advantages including high fractional free volume (FFV), good mechanical and film-forming characteristics, and excellent processability which provide for high CO₂ selectivity of the material [135]. In lieu of the aforementioned properties, pristine PIMs are usually associated with shortcomings ranging from physical aging to low CO₂/N₂ selectivity (<20) which limit their industrial application. The detrimental aging effect of PIMs is somewhat evident in TFC assemblies, especially in situations where a 90% drop in CO₂ permeance was clearly ascribed to the physical aging of the composite material [136, 137]. In order to offset the aging problem associated with TFCs, a TFC membrane codoped with a polymer of intrinsic microporosity such as the PIM-1 was hybridized with nano-MOFs (i.e., MOF-74-Ni and NH₂-Uio-66 nanoparticles) and adopted for postcombustion CO₂ capture [138]. The design of the TFC membrane comprised of three layers, i.e., (i) a PIM-1/MOF mixed matrix CO₂-selective layer; (ii) an ultrapermeable polydimethylsiloxane (PDMS) gutter layer impregnated
with MOF nanosheets that provides for CO₂ permeance in the range of 10,000–11,000 gas permeation unit (GPU), thus allowing for less CO₂ transport resistance relative to the pristine PDMS gutter layers; and (iii) a third porous polymeric substrate-layer. Furthermore, by blending the nanosized MOF particles into the PIM-1, the resulting TFC membrane assembly gave high permeation of CO₂ in the region of 4660–7460 GPU with CO₂/N₂ selectivity ranging from 26 to 33 as compared with that of the pristine PIM-1, which gave CO₂ permeance of 4320 GPU with corresponding CO₂/N₂ selectivity of 19. In addition, the PIM-1–MOF-based TFC membranes were sento exhibit enhanced resistance to aging effect, thus maintaining a constant CO₂ permeance in the region of 900–1200 GPU with CO₂/N₂ selectivity of 26–30 after 8 weeks.

Other works on PIM for CO₂ capture include the work of Bhavsar et al. [139] where ultrapermeable PIM thin-film nanocomposite membranes were anchored on microporous polycrylonitrile (PAN) supports for effective CO₂ capture. Borisov et al. [136] also carried out an investigation of gas (CO₂/N₂) selectivity in thin-film PIM-1 composite membranes where they established the potential of the membrane for adsorbing both gases. However, it was also observed that the selectivity of the membrane for each gas decreased over the aging period of the membrane. Liang et al. [140] also allotted the performance of multilayer PIM composite hollow fibers to their intrinsic microporous multilayer gutters. In addition, the studies conducted by Tiwari et al. [141] and Swaidan et al. [142] bother on the examination of the aging period, plasticization, and CO₂ adsorptive performance of a synthetic thin-film and rigid PIM-1 membranes, respectively.

Three-phase mixed matrix membranes comprising of poly (ether-block-amide (PEBA), polyethylene glycol (PEG), and nanozeolite X were produced; the effects of the PEG and/or the nanozeolite on CO₂ and CH₄ permeabilities and CO₂/CH₄ selectivities of the membranes were examined. The CO₂ permeability and selectivity of the membranes were seen to increase with feed pressure and PEG loading. However, at a pressure of 8 bar, the PEBa membrane doped with 30% PEG and 10% nanozeolite X gave the best performance with CO₂ permeability and CO₂/CH₄ selectivity 95 Barrer and 45, respectively [143].

Synthetic ionic liquid (3-di-n-butyl-2-methylimidazolium chloride (DnBMCli)) was used in modifying a sample Pebax 1657 surface as a means of strengthening the carbon-carbon bond in the mixed polymer matrix [144]. By the coating method, ZIF-8 nanoparticles produced from different precursor ratios were doped in the matrix of the IL-Pebax 1657 system in order to fabricate the mixed matrix membranes (MMMs). Tests such as SEM, DSC, FTIR, 13C NMR, TGA, and gas permeation analysis were used to characterize and evaluate the performance of the MMMs. Based on the results of the gas permeation tests conducted, increased CO₂/CH₄, CO₂/N₂, and CO₂/H₂ selectivities were observed for the modified DnBMCI-MMM relative to the

<table>
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<th>Nomenclature/ molecular formula</th>
<th>Feed composition (CH₄/CO₂/H₂)</th>
<th>X (CO₂ : CH₄ : H₂) (wt.%) or as given</th>
<th>BET surface area (m²/g)</th>
<th>Langmuir surface area (m²/g)</th>
<th>Adsorptive capacity (%)</th>
<th>P (bar)</th>
<th>T (K)</th>
<th>S CO₂</th>
<th>Q</th>
<th>Ref.</th>
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*X = CO₂ uptake

Table 1: Properties of MOFs and MOF-based membranes measured at pressures of 8.5–224.99 bar.
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<th>Nomenclature/ molecular formula</th>
<th>Feed condition (CO₂ : N₂)</th>
<th>( X (\text{CO}_2 : \text{CH}_4 : \text{H}_2) ) uptake (wt.%)</th>
<th>Low-pressure separation data</th>
<th>Adsorptive capacity</th>
<th>( P ) (bar)</th>
<th>( T ) (K)</th>
<th>( S_{\text{CO}_2} ) (kJ mol(^{-1}))</th>
<th>( Q ) (kJ mol(^{-1}))</th>
<th>Ref.</th>
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<td>2100</td>
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<td>Zn-DABCO</td>
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<td>1.87 mmol/g</td>
<td>1870</td>
<td>1902</td>
<td>7.2</td>
<td>1</td>
<td>298</td>
<td>22.4</td>
<td>[87]</td>
</tr>
<tr>
<td>Ni-DABCO</td>
<td>60–100 mg</td>
<td>2.17 : 0.51 mmol/g</td>
<td>2120</td>
<td>2219</td>
<td>8.1</td>
<td>1</td>
<td>298</td>
<td>25.8</td>
<td>[87]</td>
</tr>
<tr>
<td>Co-DABCO</td>
<td>60–100 mg</td>
<td>0.57 mmol/g</td>
<td>2022</td>
<td>2095</td>
<td>4.1</td>
<td>1</td>
<td>298</td>
<td>29.8</td>
<td>[87]</td>
</tr>
<tr>
<td>Mg/DOBDC</td>
<td>40 : 60 v/v</td>
<td>180 cc/g</td>
<td>1415.1</td>
<td>25</td>
<td>1</td>
<td>298</td>
<td>47</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>([\text{Ag}_3\text{[Ag}_5\text{(I3-3,5-Ph}_2\text{tz})_6\text{]}\text{(NO}_3)_2\text{]}_n)</td>
<td>—</td>
<td>1.6 : 1 cc/g</td>
<td>10.5</td>
<td>18.5</td>
<td>9.1</td>
<td>10.5</td>
<td>18.5</td>
<td>116</td>
<td></td>
</tr>
<tr>
<td>([\text{Ag}_3\text{[Ag}_5\text{(I3-3,5-tBu}_2\text{tz})_6\text{]}\text{(BF}_4)_2\text{]}_n)</td>
<td>—</td>
<td>0.37 mmol/g</td>
<td>1.6</td>
<td>1</td>
<td>298</td>
<td>14</td>
<td>15</td>
<td>116</td>
<td></td>
</tr>
<tr>
<td>Basolite® C 300</td>
<td>2 mmol/g</td>
<td>1706.42</td>
<td>9.4</td>
<td>0.95</td>
<td>318</td>
<td>18</td>
<td>117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basolite® F300</td>
<td>0.5 mmol/g</td>
<td>1716.46</td>
<td>2.4</td>
<td>0.95</td>
<td>318</td>
<td>19</td>
<td>117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZIF-68 15 : 10 : 75 ((\text{CO}_2\text{SO}_2\text{N}_2))</td>
<td>—</td>
<td>1.6 mol/kg</td>
<td>1220</td>
<td>41.3</td>
<td>0.9</td>
<td>298</td>
<td>30</td>
<td>33.3</td>
<td>[131]</td>
</tr>
<tr>
<td>Zn(bpta)-2-1</td>
<td>4.195 cm(^3)/g</td>
<td>51</td>
<td>8.2</td>
<td>1.2</td>
<td>298</td>
<td>23</td>
<td>34.82</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td>Cu(_2\text{L (DMA)}_4) \text{UHP-grade}</td>
<td>160 cm(^3)/g</td>
<td>1433</td>
<td>22.2</td>
<td>1</td>
<td>296</td>
<td>41.6</td>
<td>35</td>
<td>133</td>
<td></td>
</tr>
<tr>
<td>bio-MOF-11</td>
<td>10 : 90 ((\text{CO}_2\text{N}_2))</td>
<td>147 cm(^3)/g</td>
<td>1148</td>
<td>22.2</td>
<td>1</td>
<td>273</td>
<td>123</td>
<td>33.1</td>
<td>[134]</td>
</tr>
<tr>
<td>bio-MOF-14</td>
<td>10 : 90 ((\text{CO}_2\text{N}_2))</td>
<td>44.8 cm(^3)/g</td>
<td>17</td>
<td>8</td>
<td>1</td>
<td>273</td>
<td>Extremely high</td>
<td>—</td>
<td>134</td>
</tr>
</tbody>
</table>
MM and pristine Pebax 1657 membranes. Also, they asserted that the inferior CO₂ separation ability exhibited by the MMMs in the mixed-gas condition compared to the situation where pure gas was adopted for the test was influenced by the effect of plasticization in the MMMs. In addition, the modified DnBM-Pebax 1657-ZIF-8 MMMs exhibited superior CO₂/CH₄ and CO₂/N₂ selectivities at feed pressures of 2 and 4 bar, respectively. The study by Sutrinsa et al. [145] involves the comparison of the operational stability of Pebax modified with ZIF-8 for gas separation with flat sheet and composite hollow Pebax fibre membranes. Also, the modified ZIF-8 was found to be stable alongside the pristine ZIF-8 due to the hydrogen bonds and the polyamide chains present in both samples, and these were reported to have improved the stiffness of the linear glassy polymer chains, thus ensuring good operational stability of the membranes at high pressure for the flat sheet and hollow fibre membranes. In addition, the outstanding long-term stability of the hollow fibre membrane suggests that the ZIF-8/Pebax coating improved the aging resistance of the poly[1-(trimethylsilyl)-1-propyne] (PTMSP) gutter layer. The poly (ether-block-amide) (Pebax) mixed matrix membranes (MMMs) were prepared using size-tunable nanoparticles of ZIF-8 nanofillers (30, 40, 50, and 110 nm, i.e., ZIF-8-40, ZIF-8-60, ZIF-8-90, and ZIF-8-110) synthesized from 98% zinc acetate dehydrate (Zn(CO)₂H₂O) and 98% 2-methylimidazole (Hmim, C₄H₆N₂) [146]. The ZIF-8 nanofillers were produced in microemulsion by controlling the ratio of Zn²⁺ to Hmim (1 : 1, 1 : 1.5, and 1 : 2). They were then uniformly distributed in the Pebax matrix without visible agglomerations/defects at loadings of 0–20 wt.% as confirmed by FESEM. Based on the results, the ZIF-8 significantly improved the CO₂ permeability and CO₂/N₂ selectivity of the MMM. The enhanced permeability of the MMM was attributed to the induced free/pore volume of the polymer caused by the integration of larger sized ZIF-8. The resulting increase in the selectivity of the MMM was allotted to the high surface area of the ZIF-8 nanofillers, which provides more active sites for CO₂ capture with allotted to the high surface area of the ZIF-8 nanofillers, resulting in improved resistance of the polymer caused by the integration of larger sized ZIF-8. The resulting increase in the selectivity of the MMM was allotted to the high surface area of the ZIF-8 nanofillers, which provide more active sites for CO₂ capture with improved resistance to mass transfer for N₂. For 5 wt.% loading of the ZIF8-90, the MMM had the best CO₂ separation performance with a permeability of 99.7 Barrer and CO₂/N₂ selectivity of 59.6, which both gave a marginal increase in about 25% when compared to the pristine Pebax membrane.

In the work of Beni and Shaharak [147], pristine zeolites (ZIF-8 and ZIF-90) were synthesized and compared with samples of both zeolites functionalized with Li, K, and Na cations. Based on the CO₂ adsorption tests conducted, the Li-functionalized zeolites gave the highest CO₂ uptake for both zeolites and these they allotted to have been enhanced by the interactions (i.e., electrostatic and dispersion interactions) that occurred between the adsorbate and adsorbent molecules which gave rise to higher binding energies. Simulation results also revealed that, at 1 bar and 298 K, the CO₂ uptakes for the Li-functionalized ZIF-8 and ZIF-90 increased by 7 and 9 times over their pristine counterparts, thus giving values of 6 and 9 mmol/g CO₂ uptake, respectively. The Li-functionalized-ZIFs exemplified chemisorption as informed by their calculated heats of adsorption which also provides vital information for efficient regeneration of the adsorbents in pragmatic situations.

1.2.4. Microbial and Algal Seed Coats: Contextualizing Regenerative Agriculture. Along farmlands on the East Coast of Australia, efforts are being put in place by farmers to test modern approaches of combating climate change. One of such measures involves planting seeds that are coated with fungi and bacteria with the intent of capturing CO₂ from air [148]; according to reports, the plan is to sink billions of tons of carbon into farmlands. There are also speculations that the coated seeds exhibit a higher carbon capture potential than a carbon capture plant. A start-up firm, known as the Soil Carbon Company, is working on a modern technology whose origin is traceable to the University of Sydney where the annual projections on the carbon sequestration potential of the technology are 8.5 gigatons carbon or one-fourth of the global annual CO₂ emissions in a year. There are also projections that this technology can store trapped carbon for a longer time than some regenerative agricultural carbon capture technologies. Injecting microbes into crops on a farmland/plantation enhances the carbon storage capacity of plants since all plants make use of atmospheric carbon dioxide in their normal carbon cycles during photosynthesis; the absorbed carbon traverses the plant roots before ending up in the soil. However, some of the trapped carbon is fairly lost in the surrounding air. This then informed the idea of coating plant seeds with fungi and bacteria that can convert the trapped carbon into a form that can be stored much longer in soils over a long period of time, say hundreds of years. This technology is promising but is yet to gain full support for commercialization. Based on some findings, the process will enrich the soil and reduce the need for high amount of fertilizers.

Another technology that bothers on the use of microbes is microbial electrolytic carbon capture (MECC) which employs microbial electrolytic cells during wastewater treatment. The process/treatment brings about net negative carbon emissions from wastewater by simply converting the inherent CO₂ in water to calcite/limestone (CaCO₃) [149]; according to reports, the plan is to sink billions of tons of carbon into farmlands. Also, reports exist that the plan is to sink billions of tons of carbon into farmlands. This suggests that the carbon capture plant. A start-up firm, known as the Soil Carbon Company, is working on a modern technology whose origin is traceable to the University of Sydney where the annual projections on the carbon sequestration potential of the technology are 8.5 gigatons carbon or one-fourth of the global annual CO₂ emissions in a year. There are also projections that this technology can store trapped carbon for a longer time than some regenerative agricultural carbon capture technologies. Injecting microbes into crops on a farmland/plantation enhances the carbon storage capacity of plants since all plants make use of atmospheric carbon dioxide in their normal carbon cycles during photosynthesis; the absorbed carbon traverses the plant roots before ending up in the soil. However, some of the trapped carbon is fairly lost in the surrounding air. This then informed the idea of coating plant seeds with fungi and bacteria that can convert the trapped carbon into a form that can be stored much longer in soils over a long period of time, say hundreds of years. This technology is promising but is yet to gain full support for commercialization. Based on some findings, the process will enrich the soil and reduce the need for high amount of fertilizers.

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MECC contributes significantly to sustainable energy practice, owing to the fact that it takes advantage of the properties of the organic constituents of wastewater for eliminating carbon-based compounds/CO$_2$ in order to produce a precipitate (calcite) alongside H$_2$ [151]. Operators of wastewater treatment facilities are held accountable for their greenhouse gas emissions during wastewater treatment by the Greenhouse Gas Protocol Initiative. For instance, the process is energy-intensive as it requires energy for the aeration process, which in turn releases volatile compounds from wastewater, during the agitation and transportation of polluted and recycled fluids within the entire process. The electricity used in wastewater treatment gives carbon dioxide, methane, and NOx gases; the aerobic treatment step gives off N$_2$O and CO$_2$, whereas the sedimentation and activated sludge steps produce CO$_2$ and CH$_4$.

1.2.5. Adsorption: Packed Beds (Alumina/Activated Carbon/Zeolite), Graphene, and Monolith-Molecular Sieves (Carbon-Coated Substrate and Carbon-Carbon Fibre Monolith). Solid adsorbents such as zeolite/activated carbon can be employed in trapping CO$_2$ from gaseous mixtures at high pressures/temperatures. During pressure swing adsorption (PSA), gas flows through one or more packed beds of adsorbent at high pressure until the concentration of the gas progressively attains equilibrium (Figure 6). Thereafter, the bed is regenerated by reversing the pressure, whereas, in temperature swing adsorption (TSA), sorbent regeneration or gas desorption occurs by an increase in temperature. The adsorption of CO$_2$ onto solid adsorbents is not considered economically viable for the recovery of large volumes of CO$_2$ from flue gas, due to the low capacity of these adsorbents as well as their CO$_2$ selectivities [152, 153]. However, hybrid systems or a combination of several carbon capture technologies may become necessary in order to make these processes economically viable.

Zeolites are aluminosilicates with well-defined micro/ultrasmall porous structures, thermal stability, recyclability, and chemical reactivity [154]. They are rated as high-performing adsorbents [155–158]. Some zeolite networks have been tested for their abilities to trap CO$_2$ under different humid conditions, and the adsorption process was simulated using the Monte Carlo simulation [159]. Although under wet conditions, a rise in CO$_2$ uptake of pure zeolites has not been confirmed experimentally, however, there are speculations that the CO$_2$ uptake of some zeolite structures is expected to rise under moist conditions [12]. For porous adsorbents such as zeolites, CO$_2$ storage is predominately seen to be caused by adsorbate-adsorbate interactions [159], which is in contrast to the case of selective CO$_2$ sequestration that is largely influenced by adsorbent-adsorbate interactions or their chemical affinity for CO$_2$ at low pressures [160].

No doubt, zeolites are potential adsorbents for CO$_2$ capture; however, their adsorption efficiencies are usually influenced by their chemical constituents/composition, charge density, and pore size. Highly crystalline zeolites with three-dimensional pores and high surface areas can be obtained by controlling the Si/Al ratio in the zeolite matrix. The notable influence of the presence of alkali/alkaline earth cations in zeolite matrices is another subject yet to be fully explored; thus, optimizing the composition of a sample zeolite may somewhat alter its CO$_2$ adsorption capacity, which is also justified by the work of Balashankar and Rajendran [161], who optimized a zeolite screening process for postcombustion trapping of CO$_2$ under vacuum swing adsorption in order to determine the optimal conditions for high efficiency. In lieu of the myriad of approaches adopted for increasing the CO$_2$ adsorptive capacities of zeolites, they still present some shortcomings which include their relatively low CO$_2$/N$_2$ selectivity when compared with their CO$_2$ adsorption potentials/high hydrophilicity, especially in feed mixtures containing both gases. Nonetheless, the CO$_2$ adsorptive capacities of zeolites may likely decrease especially in situations where the CO$_2$/N$_2$ mixtures are entrained with moisture. Also, upon adsorption, zeolite regeneration is only achievable at temperatures (>300 °C) [162].

The CO$_2$ capture potential of zeolites has been widely discussed owing to their molecular sieving abilities and strong dipole-quadrupole/electrostatic interactions that exist between CO$_2$ and the alkali/alkaline-earth-metal cations (Li, Na, and Al) in the zeolite matrices [163]. These cations influence the heat of adsorption of CO$_2$, such that it increases with a corresponding increase in the monovalent charge density of the inherent negative charges in the material [164, 165]. Zeolites 13X and 5A have been reported to give high CO$_2$ retention/performances in the range of 3–25 wt.% at room temperature and a CO$_2$ pressure of 100% [3, 166–168]; they also recorded a CO$_2$ capture of 2–12 wt.% at room temperature and a CO$_2$ partial pressure of 15% [169–171]. Cavenati et al. [172] demonstrated the ability of zeolite 13X as a suitable adsorbent for CO$_2$; they recorded a CO$_2$ capture of 28.7 wt.% and CO$_2$/N$_2$ separation capacity of 3.65 at 298 K and 10 bar. The work of Jadhav et al. [173] bothers on the modification of zeolite 13X using mono-ethanolamine (MEA) impregnation in order to improve its CO$_2$ trapping capacity. The CO$_2$ adsorption capacity of the modified zeolite 13X was seen to be better than that of the pristine zeolite by a factor of about 1.6 at 303 K, while at a temperature of 393 K, the efficiency was seen to improve by a factor of 3.5. However, in lieu of the reduction in pore volume and surface area that ensued from the MEA impregnation, they asserted that the improved capacity of the modified zeolite 13X was due to the chemical interactions between CO$_2$ and the infused amine groups. Zeolites 13X and 5A impregnated with LiOH (LEZ-13X and LEZ-5A) were used to trap CO$_2$ under ambient conditions. Based on the BET analysis, the surface areas of the LiOH-doped sorbents were much smaller than those of the undoped zeolite. Also, the LiOH-doped zeolites gave higher CO$_2$ adsorption relative to the bare zeolite when in contact with air/oxygen. An optimization of the optimum moisture content for maximum CO$_2$ removal was carried out by correlating the measured relative humidity (RH) with CO$_2$ uptake [174].

Some recent advances in the use of graphene have also shown its potential as a suitable adsorbent for GHGs/CO$_2$. Graphene is a 2D super carbon-based allotrope with $\text{Sp}^2$
hybridized atomic layers [175]. Graphene and its derivatives are potential materials for effective CO2 capture [176–181]. According to Kemp et al. [182], this happens by reason of the grafting of compatible functional groups onto graphene layers, thus giving rise to highly stable N-doped graphene composites with surface areas in the region of 1336 m²/g and reversible CO2 capacity of 2.7 mmol/g at 298 K and 1 atm for repeated adsorption cycles. Oh et al. [183] studied the performance of borane-modified graphene; they reported a CO2 uptake of 1.82 mmol/g at 1 atm and 298 K. New hybrid systems such as mesoporous graphene oxide (mGO)-ZnO nanocomposite [184], mesoporous TiO2-graphene oxide nanocomposites [185], Mg-Al layered double hydroxide (LDH) graphene oxide [186], MOF-5-aminated graphite oxide (aGO) [187], UiO-66-graphene oxide composites [188], as well as MIL-53(Al)-graphene nanoplates (GNP) [189] have shown improved CO2 adsorptive properties over their nonhybrid counterparts. Table 3 gives a summary of the advances made in different categories of carbon sequestration technologies.

The certification of materials as good adsorbents for CO2 separation from flue gas depends on the following criteria:

(i) Adsorptive capacity: this gives information on the quantity of CO2 that can be trapped on the surface of the solid adsorbent. It is defined as the gravimetric or volumetric uptake of CO2 per unit mass of adsorbent (i.e., grams or volume of CO2/grams of adsorbent). This dictates the amount of sorbent as well as the size of the adsorbent/packed bed required for a particular operation. The adsorptive capacity of a solid adsorbent determines the energy required during the adsorbent regeneration step.

(ii) Selectivity: this is defined as the CO2 uptake ratio with respect to another gas (i.e., N2 during post-combustion CO2 capture or CH4 in CO2 sequestration from natural gas). The adsorbent selectivity for carbon-based compounds has a resultant effect on the purity of the adsorbed gas [190]. The simplest approach for estimating the selectivity of a solid adsorbent is to evaluate its adsorption profile based on the single-component adsorption isotherms of CO2 and N2.

(iii) Enthalpy of adsorption: this is the amount of energy required to regenerate the solid sorbent, which in turn impacts the cost of the regeneration process. It also measures the affinity of the material for CO2/target-substance in relation to the strength of the adsorbate-adsorbent interactions.

(iv) Chemical, physical, and thermal stabilities: excellent solid adsorbents must be able to demonstrate high stability when in contact with the contaminated streams, especially during the adsorption-regeneration cycle [191].

(v) Hydrostability: essentially, hydrosorbent stability is a necessary requirement for the sustainable performance of solid adsorbents in contact with water vapour. Furthermore, the thermal capacity and conductivity of the adsorbent are also essential properties for solid adsorbents during mass transfer operations.

(vi) Adsorption-desorption kinetics: the time taken for adsorption and adsorbent regeneration greatly relies on the profile of the adsorbate adsorption-desorption kinetics, which is determined by breakthrough curves. Adsorbents that adsorb and give off adsorbates with ease upon regeneration are more often preferred, owing to the fact that these can be achieved within shorter cycle times for small quantities of adsorbents, which in turn influences the overall cost of trapping the adsorbate.

(vii) Cost of adsorbent: since several adsorbents that exhibit excellent sorption attributes are readily available at low costs, they are rather deemed the most ideal candidates for CO2 capture. In lieu of the advantages gained from the cheap nature of these...
materials, the environmental impact of their synthetic routes is a major hurdle that needs to be overcome. As previously mentioned, some solid adsorbents that have been adopted for the trapping of carbonaceous substances/CO₂ include activated carbon (AC), single/multiwalled carbon nanotubes (CNTs), and graphenes. ACs are inexpensive, porous-amorphous structures, which possess high specific surface areas that serve as gas traps for greenhouse gas (GHG)/CO₂-uptake [192–194]. Unlike zeolites, one of the basic ills associated with the use of ACs for CO₂ adsorption is that there are no active sites for the gas to bond with the adsorbate as orchestrated by the presence of cations in zeolite. Weak interactions result in low enthalpies of adsorption and sorbent regeneration. ACs give very low CO₂ uptake at reduced pressures due to the absence of electric fields on the surfaces of ACs. Kacem et al. [195] carried out a study to test the capacity of ACs and zeolite for CO₂ separation from N₂ and CH₄ based on their regeneration potential, reusability, and adsorptivity. They observed that the CO₂ uptake for ACs was far higher than that of zeolites at pressures above 4 bar. The amount of CO₂ recovered at the AC regeneration stage was purer compared to that recovered from the zeolite samples. In addition, the ACs were found to be more stable in the presence of water vapor, thus resisting any framework collapse [196].

To improve the performance of ACs for CO₂ adsorption, amines have been found to be very effective [197–200]. Maria et al. [201] modified the surface of a microporous AC of 80% active surface via the simultaneous grafting of amine and an amide onto its surface. The work of Gibson et al. [202] bothers on the impregnation of polyamine within the pores of carbon, where the CO₂ adsorption was seen to be 12 times that of the undoped carbon. CO₂ uptake by AC has been enhanced by direct impregnation with chitosan and triethylenetetramine onto AC surface, where about 60 and

<table>
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<th>Table 3: Summary of advances made in the categories of carbon sequestration technologies.</th>
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<td>Physical absorption</td>
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<td>Chemical absorption</td>
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<td>Cryogenic separation</td>
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90% increment in CO₂ uptake were recorded at 298 K and 40 bar. The performance of NH₃-modified ACs have been investigated at 1 atm and within a temperature range of 303 to 333 K [203]; reports from the investigation showed that the calculated enthalpies of CO₂ adsorption for the modified AC and the piristine AC are 70.5 kJmol⁻¹ and 25.5 kJmol⁻¹, respectively, thus indicating that the adsorption process is largely due to chemisorption. At 303 K and 1 bar, the recorded selectivity and adsorption capacity of the NH₃-modified AC gave corresponding CO₂ uptake of 3.22 mmol/g for the NH₃-modified AC and 2.9 mmol/g for the unmodified AC [203]. CNTs are very friendly with amine solvents, such that when combined, they are very efficient in the trapping of CO₂ [204–208]. Liu et al. [204] synthesized industry-grade CNTs that were functionalized with tetraethylenepentamine (TEPA). The effect of the amine loading on CO₂ uptake, enthalpy of adsorption, and adsorbent regeneration was investigated. The TEPA-impregnated CNTs gave a CO₂ adsorption rate of 3.09 mmol/g adsorbent at 343 K. A similar investigation was conducted using 3-aminopropyl triethoxy silane (APTES) [209], polyethylenimine (PEI) [206], and di-/tri-ethanolamines [210].

2. Future Considerations for Carbon Capture Systems

No doubt, in the near future, greenhouse gas emissions will continue to constitute a global menace to the earth’s climate, her populace, and the ecosystem. However, over decades, the literature reveals that concerted efforts were channeled towards abating/controlling CO₂ emissions owing to the large volume of CO₂ released from fossil fuels. On a unit basis, the amount of other gaseous constituents can be somewhat significant, hence the need to look into trying out some of the methods developed for CO₂ capture for their likelihood of being compatible with other greenhouse gases. This then suggests that new methods or modified versions of some existing methods may become necessary in order to achieve this expectation. In addition, there is a need to have a clear understanding of the chemical structure of these gaseous constituents (HCl₃, CCl₄, H₂Cl₂, CH₄, etc.) and how porous materials can be engineered to ensure their entrapment. The framework of some choice MOFs can be tuned to make them have high selectivity with respect to a target component relative to other gases. For instance, if CH₄ is the target gas to be trapped, the matrix of a choice MOF has to be tuned to ensure its selectivity for CH₄ the same goes for membranes where high functionalities can be achieved via doping the membranes with nanoparticles or activating them with ionic liquids. This hybrid approach helps to combat the ills associated with using one type of approach per operation because a hybrid system offers the combined abilities of different blends to trap these gaseous constituents. Some of the challenges associated with CO₂ capture during post-combustion capture have also been pointed out to include low CO₂ partial pressure, high flue gas temperature, and high CO₂ concentration in the gas. Also, as already discussed, aqueous amines are suitable for acid gas absorption, but their shortcomings (high costs of solvent regeneration, low CO₂/H₂S selectivity, corrosiveness, and solvent volatility), these have spiked up a revolution in technological advances, where ionic liquids can be used alongside membranes or MOFs for improved adsorption of not just CO₂ but other greenhouse gases.

3. Conclusion

Carbon capture systems have proven to be very helpful in reducing the global carbon footprint of the earth. Based on the recent advances recorded in the use of membranes of high thermal, hydrological, and chemical stability, as well as ionic liquids, MOFs, and other solid adsorbents, it is clear that no one adsorbent is an all-time solution to all the greenhouse gas emissions. It then suffices to say that the best solution still lies in creating optimized hybrid capture systems comprising of one or more combinations of MOFs with methyl functionalized ligands [119] + inorganic/ionic liquids; bionanocomposite membranes comprising of rGO+DEA or K₂CO₃/Ca(OH)₂+DEA; and zeolite + ionic liquids, etc., for efficient trapping of greenhouse gases.

Despite the potential of each material as a stand-alone technology, the recommendation of the novel hybrid solvents often drifts towards lower energy costs, low solvent loss, low fouling tendencies, and regeneration requirements compared to those associated with conventional amine solvents and this is due to the inherent phase changes that are usually associated with ionic liquids/nonaqueous solvents and enzyme-activation systems which are all promising technologies. For mixtures of low carbon dioxide contents, chemical solvents are usually preferred to physical solvents because physical solvents give better performances at high CO₂ partial pressures.

Also, since the presence of fluorine and chlorine functional groups in polymer-/MOF-based membranes help in the adsorption of CO₂ [121], the functional groups of the adsorbents can also be tweaked in favour of their adsorptive capacities for CH₄ and other carbonaceous gases when polymers/MOFs such as polyhedral metal-organic (PMO) frameworks are being fabricated using supermolecular building blocks functionalized with halogenated solvents of chlorine and fluorine in order to boost their abilities to trap CO₂ and some light hydrocarbons including CH₄ and C₂H₆. Since a large majority of these systems have been adopted in capturing CO₂, a good insight of the underlying mechanisms that help to ensure carbon seizure in these systems or their modified forms will help tailor the properties of these adsorbents to suit their applications to other gases. Based on the findings of this review, better CO₂ adsorption is often recorded at lower temperatures and higher pressures. Furthermore, as a result of the high solubilities of some of these gases in some ionic liquids, these liquids can be selected, functionalized, and integrated into some choice adsorbents for the basic purpose of trapping any greenhouse gas of interest. This will not only help to reduce cost but will in turn maximize the effectiveness and efficiencies of modern-day greenhouse capture systems.
Data Availability

All data used to support the findings of this study are available within the article.

Conflicts of Interest

The authors are sure that there are no known conflicts of interest as regards the publication of this manuscript.

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