Results in Engineering 15 (2022) 100512

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Advanced techniques for the capturing and separation of CO_2 – A review

O.A. Odunlami [a,*], D.A. Vershima [a], T.E. Oladimeji [a], S. Nkongho [a], S.K. Ogunlade [a], B.S. Fakinle [b]

[a] Department of Chemical Engineering, Covenant University, Ota, Ogun State, Nigeria
[b] Department of Chemical Engineering, Landmark University, Omuaran, Kwara State, Nigeria

ARTICLE INFO

Keywords:
Ionic liquids
Molten carbonate fuel cells
Carbon capture
Zeolite

ABSTRACT

The review was carried out to compare the efficiencies of the advanced and modern techniques for the capturing of CO_2 and those (technologies) which are already in place. The ever-growing concern for the need to reduce and eliminate the effects of CO_2 in the atmosphere has led to major areas of CO_2 capture, over the years, to be explored and applied. Several techniques such as adsorption, absorption, cryogenic separation technique, membrane and a combination of two or more of these techniques were explored to determine which was most effective in the carbon capture process. A combination of the principles of these techniques were explored to determine how they can be applied in the advanced techniques of the CO_2 capturing and storage processes, within this new age. Absorption stands out as the most commonly used technique for carbon capture. However, it is energy intensive and depending on the solvent used (i.e., ethanol), can be corrosive to the vessel it is utilized in. The review explored advanced methods for carbon dioxide capture such as the use of ionic liquids, zeolites, molten carbonate fuel cell and integration with several other components that enhance, not only their efficiencies, but also other physio-chemical properties that encourage its advancement. These were explored in the course of writing this review paper. From the review, it was discovered that Ionic liquids, integrated with membranes, enhance selectivity towards efficient CO_2 capture. Zeolites occur naturally or are produced synthetically. They comprise of metal ions, are porous and made of certain ligands. They apply the principle of adsorption to remove CO_2 and store. Molten carbonate fuel cells operate at high temperatures (usually at 600 °C) and have CO_2 removal efficiencies of up to 60%. The review paper was, successfully, able to identify some of the major advanced technologies in the process of Carbon capture and the principles, efficiencies and cost-effectiveness were described, appropriately. From the literature, molten carbonate fuel cells were the best of the three advanced methods, with high efficiency and operations at high (and varying) ranges of temperature.

1. Introduction

Carbonaceous fuels have served as the main sources of energy supply of the world's overall energy supply [1]. Carbonaceous fuels are of three major types, which include, coal, petroleum and natural gas [2]. Due to the heavy reliant on these carbonaceous fuel sources, there tends to be a heavy release of pollutants to the atmosphere that contributes to the greenhouse effect. Compounds of sulphur and compounds of nitrogen were thought of as the main and sole contributors to the global warming effect [1]. However, studies have found this to not be entirely true. Research has shown that CO_2 (carbon dioxide) and CH_4 (methane) are the major contributors to this effect and deserve much attention in the control and elimination process of pollutants in the atmosphere.

Due to the major concern for the global warming effect, more studies have been put into place to try and control the pollution of the atmosphere and ways to improve and advance such steps, via certain technologies [3]. The amount of CO_2 in the atmosphere has since increased at an alarming rate and even with measures already put in place, there seems to be much more to be demanded in the area of research, towards eliminating this problem [1]. Research shows that, there is going to be a significant increase in the CO_2 concentration in air, by 2050, if no immediate precautions are taken to curb such effects [4].

Several steps have been taken by governing bodies such as the UN (united nations), to curb the effect of the global warming problem [4]. In 2015, the UN (united nations) arranged for a meeting in which they reached a deal which is known as the Paris agreement [4]. The agreement was that an objective of under 20 ^{O}C temperature or less (global temperature), has to be reached before the end of the century [1]. This

* Corresponding author.
E-mail addresses: olayemi.odunlami@covenantuniversity.edu.ng (O.A. Odunlami), vdenen@yahoo.com (D.A. Vershima), oladimeji.elizabeth@covenantuniversity.edu.ng (T.E. Oladimeji), soniankongho@yahoo.com (S. Nkongho), skogunlade@yahoo.com (S.K. Ogunlade), xdales@yahoo.com (B.S. Fakinle).

https://doi.org/10.1016/j.rineng.2022.100512
Received 18 April 2022; Received in revised form 20 June 2022; Accepted 21 June 2022
Available online 27 June 2022

has put most industries on notice and a lot of them that employ processes that compromise the immunity of the atmosphere to the effects of the global warming, by utilizing processes that emit large volumes of these greenhouse gases, have begun to look for alternative means to conduct operations in much safer and better ways [1]. There have been several methods that have been identified as imperative means by which CO_2 can be efficiently reduced, in terms of its generation and also removal from the source of production [4]. These methods include, the process of reducing the energy utilization, the process of increasing the energy efficiency, the use of alternative sources of energy and adopting carbon capturing techniques [1].

The main objective of this review is to identify advanced means by which CO_2 capture can be curbed. Due to the need for more efficient means by which the CO_2 should be captured, it is important that we opt for more stable means by which these separations can be done and in the most cost-effective manner [5]. The review aims to ascertain the amount of CO_2 that can be removed and eliminated and also the components of the technologies being employed in the CO_2 removal process. The best technique to approach the issue of CO_2 capture was also evaluated.

2. Literature review

2.1. CO_2 handling and storage

2.1.1. CO_2 transportation

Pipelines serve as great means to convey the CO_2, based on their structures and ability, if configured, properly, with the right dimensions to be able to withstand the pressure and velocity at which the fluid flows along the pipe or at which they are transported at [6]. The CO_2 is usually transported to places or locations that are not exposed or isolated from people or the environment [1]. The CO_2 is taken to certain areas where it can be kept in the sub-surface. There is an ever-growing need for the use of trucks and other vehicles to convey CO_2 by road, for industrial purposes. Some areas, are not as explored or are limited to coverage, due to the limitations of the pipelines, either by virtue of its physical properties or its capacity [1]. It is also relatively expensive to set-up, so it is necessary to have an alternative source of transport, other than pipelines and ships [6,7].

There are strong similarities between the CO_2 pipelines used by oil and gas industries and the natural gas industry. However, oil and gas pipelines operate within a range of pressures between 2000 and 3000 psi and natural gas pipelines operate within a pressure range of about 1000–1500 psi [6]. The use of pipelines has been a staple in the carbon transportation system by the USA, over the years. The USA has been able to confirm the importance and effectiveness of transporting CO_2 over large distances and in large quantities (almost 50–60 million tons of CO_2) per year [6]. Nigeria has been able to acquire a pipeline that has the capacity to transport natural gas, over a large distance, from their gas reserves, to other West African countries.

2.1.2. CO_2 storage

The use of geological formations in the storage and the process of securing the captured CO_2 has seen an increase, over the past few years, due to a relative increase in the release and pollution of the atmosphere by the greenhouse gasses [6,8]. Different industries utilize this process to conserve and expel unwanted CO_2 material or to recycle it for use, such as the oil, cement, iron and steel industries, power plants and food production industries [9]. Carbon capture has already been established to operate within certain principles that revolve around the adsorption process. There are two major techniques used in the process of carbon capture, which includes the direct and indirect methods [9]. In the direct method, CO_2 is mostly bounded before it leaves the source of its formation and before it pollutes the atmosphere [6,10]. This is then kept in an isolated and secure area. For the indirect technique, plants are used to collect and trap the CO_2, utilizing the process of photosynthesis which makes the entire process eco-friendly and further traps the CO_2 within the soil. There are other methods that are referred to as higher and more advanced methods in the area of transportation and storage of CO_2 ([11]; [9]. Due to the growing demand of alternative geological formations or locations for storage of captured CO_2, different methods and storage types have been utilized over the years ([11]; [6]. Geological storage processes, in operations include, the use of saline aquifers, the use of un-mineable coal seams and recycled oil and gas reservoirs [9]. A major challenge with transporting CO_2 over long distances is the cost of set-up and facilities required for the transportation process [6].

2.2. Carbon capturing techniques

Carbon capturing techniques operate through three major processes, which include, the post-combustion, precombustion and oxy-combustion techniques [1]. Carbon capture occurs on different principles and through different methods, which include adsorption, absorption, biological method, membrane, liquid-gas extraction and a combination of these principles and methods also serve as means to separate carbon, at different levels and stages [4,12].

The selection of the kind of process to be used is dependent on the material to be used and the process being operated. Some processes may require that the extraction occurs at the start of the process and some others may demand that the process of extraction is at the exhaust phase, of extraction [5]. These are characterized by the various physio-chemical properties of the materials and substances that are in use [1].

2.2.1. Post-combustion CO_2 capturing technique

Post-combustion CO_2 capture technique involves the capturing and removal process of CO_2 from the exhaust gas streams, also called the flue gas stream, before it gets into the atmosphere and causes some level of harm to the environment. It involves the removal of CO_2 after the combustion process occurs [13]. The fuel material undergoes combustion, with the presence of an air mixture (N_2 and O_2) [14].

2.2.1.1. Characteristics and issues faced while employing post-combustion technique.

I. The entire process is energy intensive [1].

II. The exhaust gas stream is at low pressure, close to the atmospheric pressure, therefore, the components of the gasses such as Sulphur oxides and Nitrogen Oxides can degrade the materials required to capture CO_2 [5].

III. It also requires a large volume of exhaust gas stream, because of the dilute nature of CO_2 in the exhaust streams. The concentration of the CO_2 in the exhaust gas streams is estimated to range from 13 to 15% [1].

It is also very feasible, as it does not necessarily alter the entire power plant process, via its adoption. It utilizes the principle of adsorption to capture CO_2. In most processes [13]. Cryogenic fractionation, absorption and membrane separation are other common principles and methods that are employed while applying pre-combustion technology [5]. Solvent-based CO_2 capturing method has been investigated and discovered to play a huge part in post-combustion CO_2 capturing process [14]. It is not very cost-effective and is quite expensive to set-up [14]. A lot of investigation has gone into post-combustion CO_2 capturing process, establishing it within the core of some industrial processes [1].

2.2.2. Pre-combustion CO_2 capturing technique

The pre-combustion CO_2 capture method, involves oxidation (partially) or gasification of fuel materials to produce CO_2 and H_2O, in power plant processes. It involves the capturing of CO_2 before combustion reaction occurs, thus leading to a cleaner fuel and gasses in the removal of CO_2 after the process occurs [1]. Gives two concrete examples, which include ammonia production and gasification of coal in power plants [13]. In ammonia processing, both CO_2 and hydrogen formed, are removed before the full processing and synthesis of the ammonia [5]. In post-combustion CO_2 process, the fuel material is converted into a carbon-free form, as in the case of hydrogen separation from syngas accompanied by the removal of CO_2 from an intermediate gas stream [5]. For a pre-combustion process, based on scalable industrial operations, for the production of hydrogen and other chemical materials, fuel materials such as coal and natural gas are transformed into syngas, which consists of H_2 and CO. through the gasification and reforming processes or through the partial oxidation process [13]. After this, the CO is moved into CO_2 by the use of water, with a noticeable increase in the production of Hydrogen, accompanied by the carbon capturing process to remove the CO_2 from the final product. It is energy intensive, due to sorbent regeneration, but comparably lower than the post-combustion CO_2 capture process [14].

2.2.3. Oxy-combustion CO_2 capturing technique

In the oxy-combustion CO_2 capturing process, CO_2 is removed via the use of pure oxygen [1]. Due to this (the use of pure oxygen for combustion instead of air), large concentrations of CO_2 are effectively captured. This process integrates the processes of pre-combustion CO_2 capturing techniques and the post-combustion capturing techniques, where a fuel material undergoes gasification in order to produce steam via the process of oxidation, with nearly pure oxygen [14]. It is an expensive process to set-up, especially in the industrial sphere, but it is an innovative and effective way in addressing the CO_2 elimination problems [14]. It is a highly innovative and comparably new technique that has been introduced to the wider industrial population [1].

2.3. Advanced separation techniques

2.3.1. Ionic liquids

Ionic liquids (ILs) are described as a kind of salt in liquid phase, usually made up of organic and inorganic anions [15]. It is usually used to describe certain salts at certain temperatures (Melting point) slightly below 100 ^{O}C [16], for most materials. ILs serve as solvents for certain reactions. They also serve a purpose in battery production and serve as good sealants [15]. They serve as good electrolytes in chemical synthesis systems. For the production of ILs, salts melt or vaporize without decomposition [17].

The van der Waals forces interacting between normal liquids is usually lesser, in strength, than the ionic bond between the ILs [17]. Due to the strong ionic bonds, these salts tend to possess high lattice energies. The ILs operate as poor electrical conductors [18]. They do not undergo freezing, at temperatures that are very low. A common impurity in a lot of ILs is water [15]. Due to several factors, such as viscosity (high viscosity), and purity (variable purity), ILs have suffered a hindrance in its application, in most industrial sectors. In order to solve the issue of the viscosity, it is imperative that a co-solvent be used to dilute the IL [18]. This is necessary to ensure that during the processes, the issue of viscosity does not impede the performance of the chemical synthesis system [15]. At certain temperatures, and at lower concentrations, ILs act as additives [18]. ILs have been used in various sample synthesis and processing methods, which include single-drop microextraction. It also includes liquid-liquid extraction [15]. There are different kinds of IL systems, which include molten salts. It also includes ionic solutions and liquid metals [15]. Due to their non-volatility, and their tunability and very viable affinity with CO_2, ILs have served the purpose of ensuring CO_2 can be properly captured and separated [18].

A very good method of enhancing the use of ILs is by integrating it with membranes, that are designed, specifically, for CO_2 capturing [16]. For the molten salts, there exists large cohesive energies and due to the fact that they operate at high temperatures, the molten salts also exhibit strong ionic conductivities [18]. The properties of the ILs such as thermal stability, solubility and viscosity can be manipulated by simply changing the configurations of the cation and anion combinations.

As stated earlier, ILs operate as compounds that are comprised of ions with melting points, usually below a temperature of 100 ^{O}C [16]. They are made up of large organic based ions connected by strong chemical bonds. ILs are usually represented in forms of abbreviations. ILs can be characterized by several parameters such as, fusion temperature, the type of ions, the number of ions, the nature of the kinds of ionic interaction between the existing ions.

The diagram in Fig. 1 describes the various applications of ionic liquids. Ionic liquids can be used as electrolytes in fuel cells, sensors and batteries. It can also be used for heat storage processes as thermal fluids. The temperature of such processes will have to be monitored to avoid thermal degradation of the fluid. It can be applied in the areas of robotics and artificial muscles. It can be used in manufacturing lubricants and fuel additives. ILs can be used in analytics, as liquid crystals, as solvents for chemical reactions and in gas separation processes.

2.3.1.1. Properties of ionic liquids.

I. Viscosity: This is highly dependent on the nature of the ion-ion interactions and the molecular size [15]. The higher they are, the higher the overall viscosity. Most ILs have high viscosities; however, some others have low viscosities [16].

II. Intrinsic Ionic Conductivity: Ultrapure water gains ionic conductivity if it is able to be infused with external ions that get characterized by water molecules [15].

III. Thermal Physical Properties: Due to their decomposition under certain conditions, ILs are often referred to as having very high thermal stability [15]. It has been discovered that high pressure CO_2 has a larger effect on the IL's melting point when compared to the effect of the atmospheric pressure CO_2 [15]. The melting point can attain heights of up to 120 ^{O}C [16]. There is a second order phase transition temperature that is related to other physical properties of the ionic liquids.

The entire idea is that the chemical and physical properties of the ILs are modified in order to obtain certain characteristics that enable the operation of certain processes, using these desired modifications of ILs. The advantages and disadvantages of ionic liquids are listed in Table 1.

2.3.1.2. Examples of modified solvents for the ionic liquid process.

I. **Hybrid solvents:** Hybrid solvents are described as involving physical mixtures of several kinds of CO_2 absorbers in order to get a desired modification or effect [15]. Mota-Lima et al. [16] describes two very good examples using amine and ILs in an aqueous solution, aimed at optimizing the solubility for a very low-viscous solvent.

II. **Deep Eutectic solvents:** Deep eutectic solvents are described as materials that are homogenous and also possess the characteristics of being eutectic [15]. They are desired in a mixture between salt and a component called, a complexing agent (CA). There is an existence of ionic-ionic bond between the interacting components as the salt operates as a hydrogen bond donor and the salt behaves as a hydrogen bond acceptor [16]. Typically employed hydrogen bond acceptors include, choline chloride [15]. IL structures have been described and found to not be greatly affected by the CO_2 combination [16]. It was also discovered that by monitoring the behaviour of CO_2 with ions, it is possible to check and connect the adsorption characteristics of CO_2 [16]. ILs and CO_2 operate and interact on a

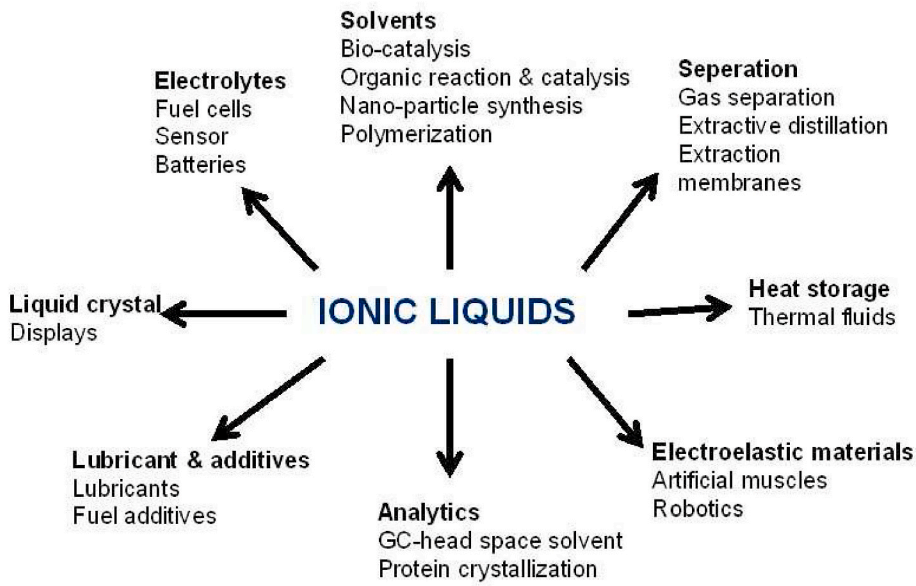

Fig. 1. Schematic representation of the general applications of Ionic liquids.
(Source: Adapted from www.intechopen.com, 2013)

Table 1
Table showing the advantages and disadvantages of ionic liquids.

Advantages	Disadvantages
I. High CO_2 absorption capacity. II. High selectivity of CO_2 from component mixtures.	II. Thermal degradation at temperatures above 100 °C. II. High Viscosity. III. Regeneration is energy-intensive. IV. In post-combustion system, large amount of solvent is required to treat the carbon di-oxide at low pressure.

physical level that can be described through several theoretical means [15].

2.3.1.3. Higher-pressure adsorption. Here, it assumed that IL- CO_2 mixture is comprised of the CO_2 at purity [16]. Research done by Mota-Lima et al. [16]; describes this combination as very essential for the separation process and in the removal of CO_2 at the desired efficiency level. Chemical adsorption involves the study of the interaction of the IL on a chemical level and the properties of the ILs that are identifiable and can be characterized to obtain at a particular level and quantity. It is a function of the IL- CO_2 efficiency of removal [16]. The use of membranes is important in separation processes as it is designed to get a specific specie, through its pores. The use of membranes has seen several advances, over the years, but has remained costly and much work is still desired in its creation [16].

2.3.2. Zeolites and metal organic framework

Zeolites can be described as a family of micro-porous alumino-silicate materials and minerals of group one and group two elements [19]. They are usually utilized as industrial adsorbents and catalysts [20]. They usually occur naturally, but can be processed using certain materials (i.e., Kaolin) and the desired type of zeolite depends on the Si/Al ratio [21]. Naturally occurring zeolites are not usually pure and are contaminated to a certain degree by other materials that are present [20]. For processes (Industrial) that require certain level of purity of other materials, zeolite usage is usually limited because of its lack of purity [5]. Under certain conditions, zeolite structures are manipulated and can transform to other minerals. Zeolites either occur naturally or are produced, synthetically [19]. The sequence of production, usually involves a mixture of sodium hydroxide with sodium aluminate in a beaker and the addition of aqueous colloidal silica to produce gel that is heated to form the final product, becomes the final part of the process [5]. Zeolites occur and are created at the intersection and cross between volcanic rocks and the available ash layer. Where they react with the groundwater, serves a platform for the zeolite formation.

Kumar et al. [22] described the adsorption process of a zeolite structure in Fig. 2. CO_2 generated from a source is selectively adsorbed on the surface of zeolite with micropores. The design and synthesis of the zeolite determines its CO_2 adsorption capacity (see Fig. 3, [23]).

Metal organic frameworks are compounds that comprise of metal ions and clusters that are designed to form a different structure [24]. They are often porous and certain organic ligands often considered as linkers or struts [19]. In a lot of cases, the pores usually are stable during the elimination phase and could be filled up by other desirable materials from the target material [24]. Valuable research has singled out metal organic frameworks as suitable materials for the capturing and storage of gases such as hydrogen and other gases like CO_2 [19]. Metal organic

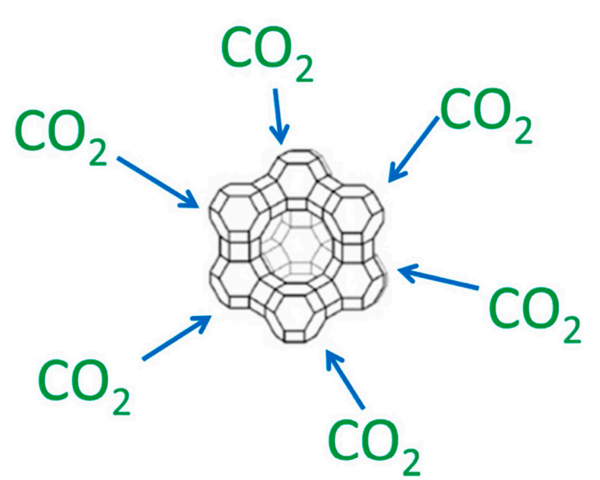

Fig. 2. Diagram representing an example of a zeolite (Zeolite A) and its structure.
(Source: Adapted from Kumar et al. [22],

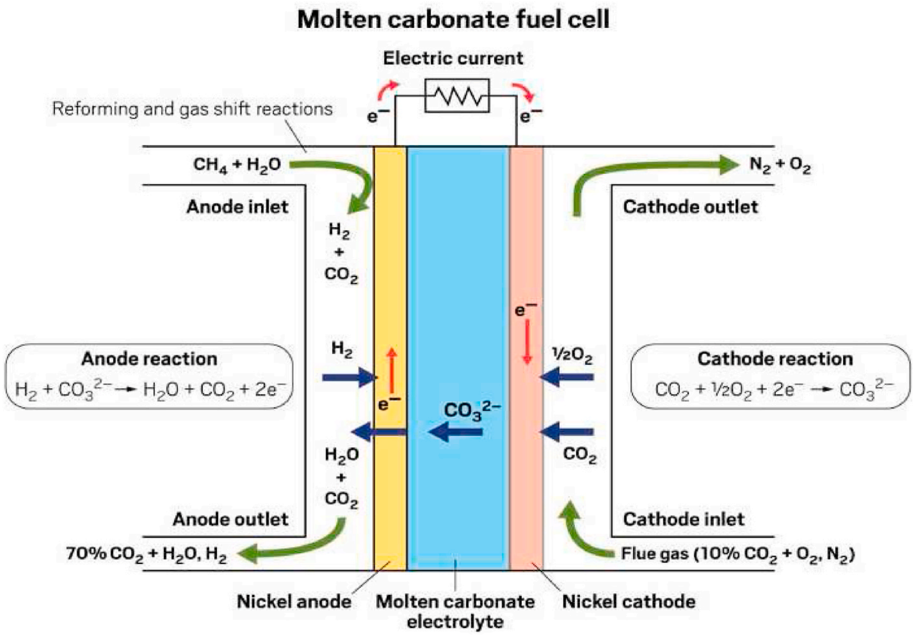

Fig. 3. Diagram representing the operation process of the Molten Carbonate Fuel Cell.
(Source: Adapted from https://cen.acs.org/energy/FuelCell-Energys-molten-carbonate-fuel/99/i11, 2021).

frameworks [24]. Metal organic frameworks are also applied in the areas of purification, gas separation and in the synthesis of capacitors and solids that are good conductors. Zeolites assist in the synthesis of the metal organic frameworks [19]. The advantages and disadvantages of using zeolites and MOFs are listed in Table 2.

When metal organic frameworks are integrated with zeolites, the product is a viable material that helps in the adsorbing process, that is desirable by the industries [24]. Ligands in the metal organic frameworks, due to their nature, bind in a reversible manner [19]. The viability of these metal organic frameworks (integrated with zeolites) lies in its ability to produce highly efficient extraction of gases from the target material [24].

The CO_2 capturing process provides a platform for the storage of these carbon (carbon monoxide and carbon dioxide), but the storage process has been a difficult subject, over time. In the Chemosorption process, it involves the chemical bonds between the adsorbate molecule and a specific surface. This method has been in place for a long period of time. The process involves the transfer of aqueous amine solution through an adsorption equipment (tower) [19]. Simultaneously, exhaust flue gas (containing CO_2) is fed from below the equipment's structure [25]. The mechanism ensures that CO_2 is separated from the exhaust flue gas [19]. This process employs the basic adsorption principle in the separation technique process.

The packings between the top and the bottom sections of the tower ensure that there is a uniform separation of the CO_2 and other desired gas, from the flue gas [19]. In the physisorption process, it involves the employment of utilization of van der Waals forces. Zeolites display high adsorption capacities and can operate within high temperature situations [19]. Zeolites have been applied even in the electricity operating system. There are other various uses of the zeolite materials, due to their chemical and physical properties that makes them suitable for adsorption processes [19]. The zeolites (synthetic) are formed based on certain criteria and the pore size requirements [25].

Table 2
Table showing the advantages and disadvantages of zeolites and MOFs.

Advantages	Disadvantages
I. Good mechanical, thermal and chemical stability.	I. Regeneration process is energy-intensive.
II. Low energy requirement, in the adsorption process.	II. High cost of implementation.
III. Good flexibility.	
IV. Ultra-high porosity	
V. High surface area.	

2.3.2.1. Properties of zeolites. These properties include:

I. Porosity [19].
II. Cation exchange [19].
III. Surface area [25].
IV. Chemical composition [26].
V. Stability of the structure [19].
VI. Heat adsorption [26].

Zeolites are designed with specificity and selection is geared towards the desired material, which in this case is the CO_2 [27]. This is also heavily influenced by the Si/Al ratio, which helps to determine the type of zeolite being formed [27]. Temperature and pressure requirements also help to determine the nature and the overall design of the zeolite to be made [25]. Kinetic properties also play an imperative role in dictating the nature of the zeolite material [27].

2.3.3. *Molten carbonate fuel cells*

These are fuel cells that carry out their operations at very high temperatures (usually at 600 °C) [28]. They have received a lot of research attention and are geared towards the industrial and manufacturing sectors, where they would play huge roles in the operation processes. Due to the fact that they operate at such high temperatures, metals can be utilized at the cathode and can also be utilized at the anode [23]. This arrangement proves to be cost-effective and efficient in nature. The efficiency of the molten carbonate fuel cell is, most often, the most desirable effect, compared to other examples of the most used methods (i.e., Phosphoric acid fuel cells) [23].

High efficiencies, up to 60%, can be obtained, compared to the usual 37–42% of Phosphoric acid fuel cell [28]. Unlike other fuel cells, molten carbonate fuel cells do not need an external reformer to transform energy-dense fuels to hydrogen. Molten carbonate fuel cells operate at very high temperatures and as such, these fuels are transformed to hydrogen, within the fuel cells [21]. The process associated with this is referred to as internal reforming. It is a cost-effective process [28]. Molten carbonate cells are not as prone to the effect of poisoning by carbon compounds such as carbon monoxide and carbon dioxide. For the most part, fuel can be generated from these and processed to ensure that they are effective in carbon capture processes [21]. This makes it attractive for use by various industries and industrial processes, in general. The biggest and most problematic drawback in the use of the modern molten carbonate fuel cell technology, is the issue of durability [28]. The cell life and its stability are greatly affected by the temperature ranges that they are operated within and the corrosive electrolyte utilized [28].

There have been several models of the molten carbonate fuel cells, presented over the years, most notably, the one presented by the German company, MTU Friedrichshafen, in 2006, at the Hannover fair [23]. Much research has gone into developing new and improved ways of creating desirable processes geared towards optimizing the entire process of the Molten carbonate fuel cell operation [23]. Molten carbonate fuel cells operate by utilizing carbonate salts as electrolyte. The temperature ranges are set, in the process (600 °C and at much higher ranges) [28]. The salts heat up and melt, and conduct CO_3 (carbonate ions), with interactions between the anode and the cathode [28]. The reaction at the anode involves hydrogen, reacting with ions to give water, CO_2 and electrons, during the process.

Desideri et al. [28] developed a cell model using a Fortran library to carry out simulation of the process (cell block). A calculation sheet was utilized, using the mass balance equilibrium for molten fuel carbonate fuel and the voltage was estimated using Nernst's equation [28]. The goal, by Desideri et al. [28]; was to achieve high amount of CO_2 to reach high efficiencies of up to 60% of the generated CO_2 [28]. The created model utilizes certain inputs such as pressure, temperature and flowrate and the fuel cell processing parameters. The desired outputs were fuel, oxidant and CO_2 and outlet flowrate compositions. CO_2 efficiency is modelled to the point where it relates to the CO_2 utilization and processing. This is given by the formula, $\eta_{rem} = CO_{2utilised}/CO_{2in}$

The CO_2 processing data and the removal efficiency removal efficiency were essential determining the best method for the selection of the appropriate cell size, for the modelled separation process [21]. Desideri et al. [28] determined that an increase in the cell size leads to an increase in the processed CO_2, and also, heat generation tends to experience an increase [21]. The exhaust temperature also experiences an increase of CO_2 processed and the outlet gas temperature, as against the cell area, helped to draw out several conclusions which suggest that most of the heat produced (almost 98% of it), is being found in the exhaust flue gas and the rest of the 2%, is left to the atmosphere [28]. Improvements to this model were made, overtime. This includes, anode and the cathode recirculation process, which enables the model's optimization. It uses a recycling technique, where the cell gets to operate with the previously developed CO_2 processing formula, but also reduces the dependency on the oxidant factor, which benefits the fuel cell life and optimizes its performance [23].

To improve the system and model, several other factors were added, such as reforming sector, treatment section and heat exchangers [23]. The major drawback to the recirculation process is the consumption of energy as it relates to compressors that characterize the inlet pressure [23]. The model generated a result of 82.2% CO_2 purity that indicated the effectiveness of the system [28]. Other systems, such as amine-based processing systems offer higher efficiencies (up to 95%) [28]. The difference remains the amount of energy utilized and consumed, operating the amine-based systems [28]. The molten carbonate fuel cell utilizes less energy and delivers high efficiencies, which enables it to be a very viable industrial model. Table 3 shows the various advantages and disadvantages of using molten fuel cells.

Table 3
Table showing the advantages and disadvantages of using molten fuel cells.

Advantages	Disadvantages
I. Resistant to impurities from gas stream.	I. Poor durability.
II. Good CO_2 capture efficiency.	II. Thermal degradation at high operating temperatures.
III. Can utilize processed CO_2 as fuel.	
IV. It is not prone to poisoning.	

2.3.3.1. General benefits of ionic liquids, molten carbonate fuel cells and zeolites and membranes. For the molten carbonate fuel cells, they operate at very high temperatures (up to about 600 ^{O}C), which makes them suitable for processes that are operated within these temperature ranges and also desire some level of thermal stability, while adsorbing the desired gas [28]. They are also cost-effective, as they are not too expensive to set-up [23]. The efficiency level is high, as they deliver at up to 60% efficiency, while being operated at these high temperature ranges (compared to the 37–42% of phosphoric acid fuel cell) [28]. The molten carbonate cells are not as prone to poisoning as other fuel cells [28].

For the zeolites, they occur naturally and can be synthetically developed to suit the desired specificity of the developer [19]. The Si/Al ratio determines the type of zeolite being developed and this could be adjusted to get the required effect for CO_2 adsorption [5]. Zeolites also address the issue of specificity, as previously stated. They are highly efficient in the removal of CO_2 and other desired gases [19].

For the ILs, they serve as solvents for several industrial process, under the desired conditions [16]. They also serve the purpose of acting as very good sealants, in industrial processes [18]. They are essential in the battery production process. ILs serve as good electrolyte sources in chemical synthesis systems and operations [18]. At lower temperatures, they act as additives in several industrial processes [16].

Limitations of ionic liquids, molten carbonate fuel cells and zeolites and membranes

For the molten carbonate fuel cells, the cell life is affected by the temperature ranges and is influenced by the timing of the temperature [28]. Under high amount of temperature, and for a long period of time, the durability of the cell decreases as a result of the amount of heat utilized [28].

For zeolites and membranes, the temperature range limits its utilization. At higher temperature, the zeolites may suffer ineffectiveness [19]. The specificity of zeolites can also limit it to certain types of gases to be adsorbed [5].

For ILs, they exist as poor electrical conductors. For processes that require such, this may serve as a hindrance to the process [16]. They have a common impurity, in water. They suffer hindrances in application such as viscosity (high viscosity), and purity (variable purity) [18].

3. Conclusion

Carbonaceous materials are the major materials in the energy and electricity generation processes and most industries utilize these as sources for power during their operations. There are many recommendations for the use of alternative resources and several substitute operations that require the minimization of the reliance on these materials. However, despite all efforts being put in place, there still seems to be a growing demand and utilization of these carbon sources that harm the atmosphere and as a result, the earth. The review takes all of these into consideration and goes a long way in identifying ways by which these pollutants and their global warming effects, particularly, the effect of CO_2, by the use of ILs, molten carbonate fuel cells and zeolites and membranes. It was discovered that the molten carbonate fuel cells operate at very high temperatures (up to about 600 ^{O}C), which makes them suitable for processes that are operated within these temperature ranges and also desire some level of thermal stability, while adsorbing the desired gas. They are also cost-effective, as they are not too expensive to set-up. All of these made them viable for CO_2 capture and removal. It was discovered, also, that zeolites and membranes address the issue of specificity, as previously stated. They are highly efficient in the removal of CO_2 and other desired gases. In addition, ILs serve as solvents for several industrial process, under the desired conditions. They also serve the purpose of acting as very good sealants, in industrial processes. They are essential in the battery production process. ILs serve as good electrolyte sources in chemical synthesis systems and operations. At lower temperatures, they act as additives in several industrial processes. All of these make these highlighted processes very viable means for CO_2 capture and removal. From the literature, molten carbonate fuel cells were the best of the three advanced methods, with high efficiency and operations at high (and varying) ranges of temperature.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Z. Zhang, et al., Carbon Capture, 2018, p. 2018.
[2] B. Praveen, P. Peter, W. Jennifer, CO_2 capture from the industry sector, Prog. Energy Combust. Sci. 63 (2017) 146–172.
[3] C. Amita, B. Ashok, A novel ionic liquid for carbon capture decomposition of HI for production of hydrogen in SI thermo-chemical cycle view project oil removal from industrial effluents view project, Athens J. Sci. 2 (3) (2021).
[4] A. Azzouz, et al., OH-enriched organo-montmorillonites for potential applications in carbon dioxide separation and concentration, Separ. Purif. Technol. 108 (2013) 181–188, https://doi.org/10.1016/j.seppur.2013.02.006. Apr. 2013 3 Oct.
[5] M.N. Kajama, et al., Experimental study of carbon dioxide separation with nanoporous ceramic membranes, Energy Sustain. V (2014), https://doi.org/10.2495/esus140551, 16 Dec. 2014. (Accessed 3 October 2021). Accessed.
[6] F. Babarinde, et al., A review of carbon capture and sequestration technology solid waste management view project materials engineering view project a review of carbon capture and sequestration technology, J. Energy Technol. Environ. 2 (2020, 23 Dec) (2020) 1–11, https://doi.org/10.37933/nipes.e/2.2020.1. (Accessed 4 October 2021).
[7] R. Christopher, Current commentary; carbon capture and storage, Sci. Prog. 95 (4) (2012) 473–483.
[8] L. Howard, Why can't we just burn hydrogen? Challenges when changing fuels in an existing infrastructure, Prog. Energy Combust. Sci. 84 (2021), 100907.
[9] S. Suliestyah, I. SariI, Effect of temperature and time of carbonization on coal-based activated carbon adsorption, IOP Conf. Ser. Mater. Sci. Eng. 1098 (6) (2021), 062020, https://doi.org/10.1088/1757-899x/1098/6/062020, 1 Mar. 2021. (Accessed 3 October 2021).
[10] R. Edward, M. Hari, M. Aaron, V. Peter, K. John, The outlook for improved carbon capture technology, Prog. Energy Combust. Sci. 38 (5) (2012) 630–671.
[11] W. Meihong, O. Eni, Special issue on carbon capture in the context of carbon capture, utilisation and storage (CCUS), Int. J. Coal Sci. Technol. 4 (1) (2017) 1–4.
[12] S. Roussanaly, R. Anantharaman, K. Lindqvist, H. Zhai, E. Rubin, Membrane properties required for post-combustion CO_2 capture at coal-fired power plants, J. Membr. Sci. 511 (2016) 250–264.
[13] S. Shafie, et al., [EMIM][Tf2N]-Modified silica as filler in mixed matrix membrane for carbon dioxide separation, Membranes 11 (5) (2021) 371, https://doi.org/10.3390/membranes11050371, 19 May 2021. (Accessed 3 October 2021).
[14] T. Tomioka, et al., Peer-Review under Responsibility of GHGT." Carbon Dioxide Separation Technology from Biogas by "Membrane/Hybrid Method, 2013, https://doi.org/10.1016/j.egypro.2013.05.219. (Accessed 3 October 2021).
[15] S. Xiong, et al., Ionic liquids-based membranes for carbon dioxide separation, Isr. J. Chem. 59 (9) (2019) 824–831, https://doi.org/10.1002/ijch.201900062, 25 Aug. 2019. (Accessed 3 October 2021).
[16] A. Mota-Lima, et al., Review—high-pressure carbon dioxide separation using ionic liquids: a CO2-electrocatalysis perspective, J. Electrochem. Soc. 168 (8) (2021), 086502, https://doi.org/10.1149/1945-7111/ac085d, 1 Aug. 2021. (Accessed 2 October 2021).
[17] S. Salmon, et al., Enzyme technology for carbon dioxide separation from mixed gases, IOP Conf. Ser. Earth Environ. Sci. 6 (17) (1 Feb. 2009), 172018, https://doi.org/10.1088/1755-1307/6/17/172018. (Accessed 3 October 2021).
[18] A. Esmaeili, et al., Assessment of carbon dioxide separation by amine solutions using electrolyte non-random two-liquid and peng-robinson models: carbon dioxide absorption efficiency, J. Construct. Mater. 2 (3) (2021), https://doi.org/10.36756/jcm.v2.3.10, 27 Apr. (Accessed 3 October 2021).
[19] M. Ghalia, Y. Dahman, Development and evaluation of zeolites and metal-organic frameworks for carbon dioxide separation and capture, Energy Technol. 5 (3) (2016) 356–372, https://doi.org/10.1002/ente.201600359, 1 Sept. 2016 2 Oct.
[20] S. Elsaidi, et al., Dual-layer MOF composite membranes with tuned interface interaction for postcombustion carbon dioxide separation, Cell Rep. Phys. Sci. 1 (5, May 2020) (2020), 100059, https://doi.org/10.1016/j.xcrp.2020.100059, 3, 10.
[21] P. Goh, et al., Surface modifications of nanofillers for carbon dioxide separation nanocomposite membrane, Symmetry 12 (7) (2020) 1102, https://doi.org/10.3390/sym12071102, 2 July 2020. (Accessed 3 October 2021).
[22] S. Kumar, R. Srivastava, J. Koh, Utilization of zeolites as CO_2 capturing agents: advances and future perspectives, J. CO2 Util. 41 (2020), 101251, https://doi.org/10.1016/j.jcou.2020.101251.
[23] C. Bettenhausen, Can fuel cell energy's molten carbonate fuel cell help solve the CO_2 problem? Acs.org (2021). cen.acs.org/energy/FuelCell-Energys-molten-carbonate-fuel/99/i11.
[24] R. Honeywell, et al., Carbon Dioxide Separation with Novel Microporous Metal Organic Frameworks, 2014, 2014.
[25] J. Lin, Novel Inorganic Membranes for High Temperature Carbon dioxide Separation, University of Cincinnati, US, 1 Feb 2003.
[26] A. Arjuva, Processing and Performance of Zeolites for Efficient Carbon Dioxide Separation, 2015.
[27] Sandra E. Kentish, et al., Carbon dioxide separation through polymeric membrane systems for flue gas applications, Recent Pat. Chem. Eng. 1 (1) (2010) 52–66, https://doi.org/10.2174/1874478810801010052, 9 Jan. 2010. (Accessed 3 October 2021).
[28] U. Desideri, et al., MCFC-based CO2 capture system for small scale CHP plants, Int. J. Hydrogen Energy 37 (24, Dec. 2012) (2012) 19295–19303, https://doi.org/10.1016/j.ijhydene.2012.05.048, 3 Oct.