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Comparative Analysis of Metal-Organic Frameworks (MOFs), Amine Scrubbing, and Zeolites for Carbon Dioxide (CO_2) Capture

Aahan Prashant
aahan.prashant@gmail.com

ABSTRACT

The paper has discussed the use of metal organic frameworks (MOF) and compared it with traditional methods for carbon capture.Evaluates whether MOFs may offer advantages over amine scrubbing and zeolites under specific carbon-capture conditions. The paper has discussed the advantages and disadvantages of these methods and also looks at the feasibility to implement Metal organic frameworks in the field of carbon capture in the future. In addition, the study takes into account the drawbacks of MOFs, such as their expense, durability over time and difficulties in implementing them on a broad scale. This study evaluates whether MOFs are a viable next-generation carbon capture option, and their potential contributions to the advancement of direct air capture technology. This is achieved by evaluating the benefits and drawbacks of each approach.

Keywords

Global warming; Carbon cycle; Carbon capture systems; Amine scrubbing; Zeolites; Metal-organic frameworks (MOFs); Organic compounds; Chemical absorption; CO_2 adsorption; Gas separation; High surface area; Tunable pore structure; CO_2 selectivity

INTRODUCTION

The Global Warming Problem

Global warming is a key issue that everyone is facing worldwide. It is the average increase in global temperatures for a longer period of time (Houghton, 2005). Global warming is caused by the increasing concentration of carbon dioxide (CO_2) and other greenhouse gases that trap heat in Earth's atmosphere. This has resulted in the higher global average temperatures since the industrial revolution which began in 1750. Although there are natural fluctuations in the Earth's global temperature, human activities have driven the current era of global warming. This includes burning of fossil fuels, such as coal, oil, gasoline and natural gas. In the United States, the largest source of greenhouse gases is transportation, followed closely by electricity production and industrial activity (Macmillan and Turrentine 2026). This has resulted in several environmental impacts. This includes an increase in average global temperatures, the ocean getting warmer, the ice sheets shrinking, intensifying natural disasters, glaciers decreasing and sea levels rising (Nasa, n.d.). All of these factors could cause unrest as many lowlying countries could be flooded and be faced with pre-existing resource scarcity conflicts. Some of these resources include crops, drinkable water, livestock and food.

Carbon Cycles

The carbon cycle is a significant biogeochemical cycle. It involves the continuous movement of carbon between the atmosphere, land, oceans and living organisms. This cycle plays a pivotal role in regulating the planet's temperature and supporting life. Heat is trapped in the Earth's atmosphere by greenhouse gases, such as carbon dioxide (Houghton 2005). Excess greenhouse gas emissions which are primarily from human activities, such as burning fossil fuels, can disturb the carbon cycle and increase global warming.

According to Earth's history, the amount of CO_2 in the atmosphere has changed. There have been periods with significantly higher and subsequent periods with lower amounts of CO_2 . In saying that, there is one factor that has remained constant: as CO_2 increases, temperatures rise too. The ocean is a significant contributor in terms of maintaining levels of CO_2. However, when temperatures increase the ocean releases back the absorbed $CO_{2.}$ This can be problematic as it causes greater accumulation of greenhouse gasses in the atmosphere(Nasa, n.d.).

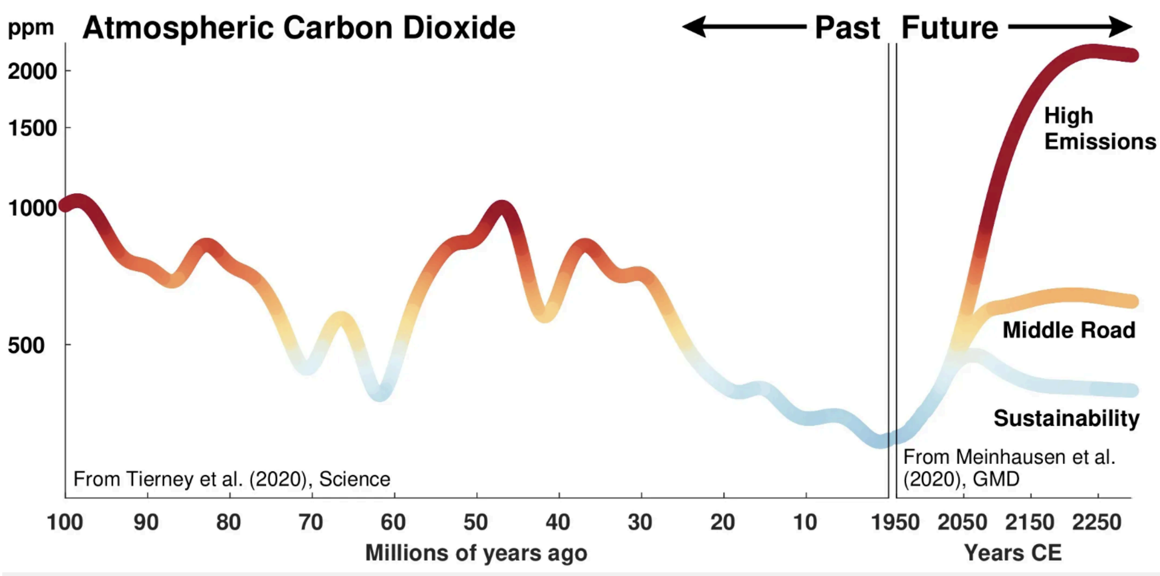

Figure 1: The Change in Atmospheric Carbon Dioxide Over the Years (Credit: Jessica Tierney/University of Arizona,2020)

The graph highlights past carbon dioxide concentrations (on the left side) compared to possible future emissions scenarios (on the right side). The rate of current emissions is much faster and it is occurring over decades. If emissions continue, carbon dioxide levels could meet or exceed values that are associated with past warm climates.

The Problem of Carbon Capture

In the past few years many attempts have been made to reduce CO_2 emissions. However, not many obvious results have been achieved. CO_2 is a greenhouse gas and a potential carbon source, as CO2 can be used for raw materials to make things, such as fuels, chemicals and plastics. Thus, there is grave importance in effectively capturing and potential use of CO_2. Carbon capture and storage technology (CCS) essentially refers to capturing and storing CO_2, and the process of removing it from the atmosphere. Carbon capture is generally used and accepted worldwide. Its importance is deeply rooted and linked to its adverse effect on global warming. If carbon capture and CCS technologies were not implemented, CO_2 levels and global warming would continue to increase.

Traditional Methods of CO_2 Capture

There are several methods to capture CO_2. Each has their advantages and drawbacks. Some of the most prominent capture methods include Amine scrubbing and the use of Zeolites. Amine scrubbing is also known as amine gas treating, gas sweetening or acid gas removal. It is the process of removing hydrogen sulfide (H_2S) or carbon dioxide (CO_2) from the air (Loachamin et al., 2024). Another word for Zeolites are Solid Adsorbents. They have a unique structure and are made of silicon and aluminum atoms that form three-dimensional networks with nanometer-sized pores. These pores allow for selective adsorption of CO_2 molecules. Thus, making them ideal candidates for carbon capture.

The underlying issue is the problem that is associated with these traditional methods. This can include the amount of energy that is required in order to use that method of capture. This process means separating CO_2 from other gases, such as nitrogen, water vapour and hydrogen. Therefore, it would cause a negative feedback loop, as most of our energy in the modern day comes from non-renewable sources. For example, coal, oil and natural gas. This would release more CO_2 back into the atmosphere and render the absorption method futile.

Another problem which is related to using traditional methods is the financial burden. There are several economic costs that are linked to carbon capture systems (CCS). The capital costs that are associated with carbon capture technologies are significantly high. It can range from $36 to $90 per ton of carbon dioxide which has been captured. The costs can vary depending on the type of technology used, the size of the capture facility, and the location of the site. For example, post-combustion carbon capture technologies tend to have higher capital costs than pre-combustion technologies. Additionally, the more a carbon dioxide facility is trying to capture, the higher the capital costs will be. However, some experts believe that these costs could be reduced in the future as the technology improves and carbon capture systems become more commercially available (Veloso, 2023). These can be substantial costs as they can include initial investment, operational expense and storage (Sustainability directory, 2025). The economic cost includes the construction costs for CCS. These require specialised equipment and capture facilities. Building these carbon capture facilities would require a significant amount of money and time, and these facilities would have to be outfitted with specialised CSS systems and technology. In addition, the transportation and storage costs would be significant (Sustainability directory, 2025).

The final major problem is the scale and technology used for the carbon capture system. This is a huge amount of the current technology which is used for carbon capture and it may have reliability and longevity issues. Carbon capture systems have to process massive amounts of CO_2 from factories or power plants, since large volumes of gas must be treated, equipment such as pipes, filters and pumps must run continuously for years. This would require constant replacement and could have potential reliability issues if not replaced. Although carbon capture has been conceptualised and implemented, it is still in its early stages of development relative to the scale at which it is needed (Sustainability Directory, 2025). The number of operations of CCS facilities is limited and this imposes a problem. Furthermore, the variability of the Carbon capture system performance is another hindrance, as no carbon capture method has 100% efficacy.

Metal-Organic Frameworks

Metal organic frameworks (MOFs) are a class of 3D materials that are made up of metals which are connected by organic MOF ligands. We can think of the metals and organic compounds as building blocks that form these MOF structures. There are over 90,000 different metal organic frameworks that are grouped into various different families. Metal organic frameworks are strong, porous materials that are part of organic frameworks. Metal ions act as clusters which are linked by 'organic linkers' - creating 3D frameworks. Pores are the gaps in the linked metals and organic linkers (Wood and Force n.d.). These pores can range in size from a few nanometers to several nanometers in diameter.

Metal organic frameworks have been revolutionary in the field of Chemistry. This was noticed in October 2025. Professor Susumu Kitagawa, Professor Richard Robson and Professor Omar Yaghi won the Nobel prize in Chemistry for the development of metal-organic frameworks. MOFs are very useful in the field of carbon capture due to their surface area to size ratio. They have extremely high porosity and surface area, up to 7,000 m^2/g. In other words, the surface area of one gram of metal-organic framework could cover an entire football field.

Many modern day carbon capture technologies, including membrane separation, chemical absorption, such as amines, carbonates and ionic liquids, and low- temperature separation can face significant challenges. For instance, high costs, low efficiency, susceptibility to amine loss and degradation and complex preparation processes. On the contrary, solid adsorption of CO_2 using metal organic frameworks have gained prominence as viable candidates due to their unique structural characteristics. This includes high specific surface area, chemical tunability, and stability (Fan et al., 2025). These desirable properties attract significant attention in the fields of CO_2 gas adsorption.

Aims and Goals of The Paper

This research paper discusses how Metal organic frameworks can be used for CO_2 capture and how it compares to other traditional methods of carbon capture, such as amine scrubbing and zeolites. It seeks to evaluate the advantages and disadvantages of each method focusing on factors, such as efficiency, energy requirements and practical application. The goal is to determine whether MOFs offer a more effective and sustainable alternative for carbon capture and to assess their potential for future large-scale use.

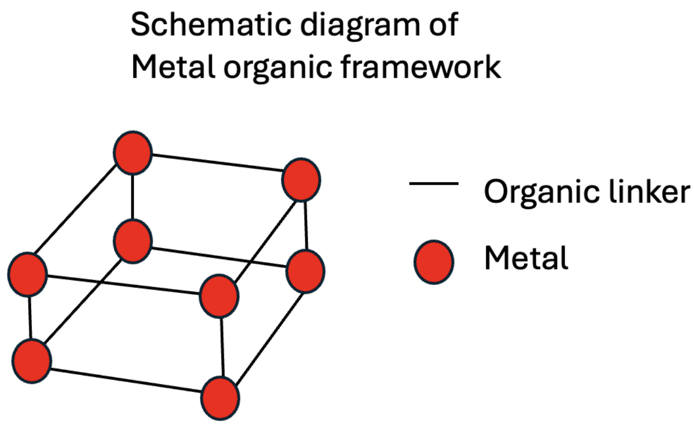

Figure 2: Diagram showcasing metal organic framework and how they are constructed with organic linker molecules holding together the metal or metal clusters.

This paper will explore and analyse the use of Metal organic frameworks for the adsorption and absorption of CO2 from the atmosphere and how it compares to other methods such as amine scrubbing and zeolites. It will discuss the need for the alternative method and why these current methods may not suffice. Furthermore, the study will explore the economic feasibility of MOFs and their future potential use. It will analyse specific types of MOFs, how they can have different uses and how their open porous structure allows for easy CO2 intake.

LITERATURE REVIEW

2.1 Traditional methods

2.1.1 Amine Scrubbing

There are two main traditional methods of CO_2 absorption. First is known as Amine scrubbing. It is now the most widely used technique for capturing CO_2. The standard absorption or stripping method for removing CO_2 and H_2S from natural gas and other fuel gases is the foundation of amine scrubbing for CO_2 capture from combustion gas. The method for sweetening natural gas that Bottoms (1930) patented can be viewed in Figure 3. This method has been used in hundreds of plants to treat natural gas and hydrogen with aqueous monoethanolamine (MEA) or other common amines, such as methylamine and aniline (Rochelle 2016).

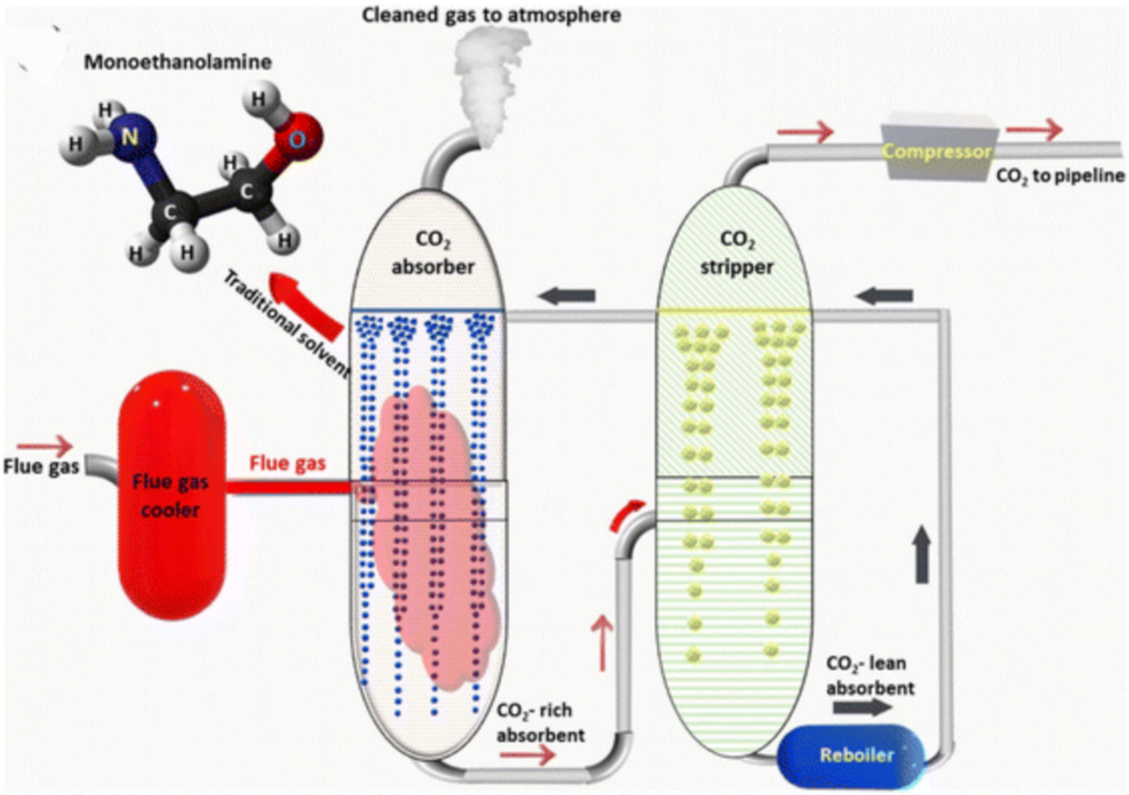

Figure 3: Post-combustion technology involves cooling hot flue gas before directing it to an absorber unit that typically contains a monoethanolamine solvent as the traditional sorbent. Then, the CO_2-rich absorbent is sent to a stripper unit to release the CO2 gas. Whilst, the CO2-lean absorbent is recycled back to the absorber unit. Finally, the pure CO2 is compressed and dehydrated for transport via pipelines and for storage purposes. This figure is adapted with permission from "Recent advances in carbon capture storage and utilisation technologies: a review", Environmental Chemistry Letters, 2020 (Osman et al., 2020).

Amines are chemicals that can be described as derivatives of ammonia1 where one or more of the hydrogen atoms have been replaced by an alkyl-2 or aryl-3 group. Amines can be classified as primary, secondary or tertiary depending on whether one, two or three of the hydrogen atoms of ammonia have been replaced by organic functional groups (Shao & Stangel 2009). Amine scrubbing is widely used due its developed process, operational convenience, high absorption capacity and its prominence as it occupies over 60% of the current Carbon capture market. In natural gas processing, an 'amine' is an aqueous solution containing several alkylamines (CarverPump, 2021). Amine scrubbing systems have two main sections: absorption and stripping.

In Amine scrubbing, natural gas is referred to as 'sour gas' as it has high concentration of CO_2 and H_2S. In absorption the solid and liquids must be removed from the sour gas, so the gas goes through an inlet separator. Then, it is fed through a contractor column. In the contractor column, there are bubble caps, which allow gas to rise from tray to tray. The sour gas enters the column from the bottom. As the sour gas rises, it comes into contact with the liquid amines. The amines absorb the CO_2 and then H_2S. Then, the gas reaches the top and most of the CO_2 and H_2S is absorbed (CarverPump, 2021).The natural gas has been treated by removing CO_2 and H_2S impurities, allowing it to meet quality requirements for further processing, transportation, and industrial use.

The main advantages of using amine scrubbing in the modern CCS market is their strong selectivity for CO_2. This means that Amines strongly prefer to bind to CO_2 rather than other gases, such as nitrogen and oxygen. This means that it can be used at a high rate as it only targets specific gas molecules, such as CO_2. Another main advantage to Amine scrubbing is that some reactants are more effective than others in amine scrubbing for CO_2 capture. Researchers identify aqueous monoethanolamine (MEA) as the most commonly used solvent for the purpose of amine scrubber CO_2 absorption. Overall, this removes 85% of carbon dioxide from the atmosphere. Another main benefit is the reusability of amines. They are not a one time use solution, they can be recycled and stripped of the CO_2 and H_2S that they absorb. The process by which amine regeneration occurs is called calcination.

2.1.2 Zeolites

Zeolites are regarded as crystalline alumino-silicate sorbents(Zeolites have many microscopic pores that provide adsorption sites where CO_2 molecules can attach). They are a type of porous inorganic material made of aluminum, silicon and oxygen (that means: aluminosilicates). Zeolites are specifically made to adsorb, separate and/or exchange molecules and ions with different geometry and porosity. The increasing levels of atmospheric CO_2 which is primarily due to human activities can pose a serious threat to global climate stability. Effective CO_2 capture and sequestration are essential to mitigate these environmental impacts. Among the various materials explored for CO_2 capture, zeolites have garnered significant attention because of their high surface area, adjustable pore structures and chemical stability.

In terms of zeolites, it is important to take into account their surface area. This is because it is the amount of internal surface within their porous structure. Zeolites have many microscopic holes and they have many sites where CO_2 molecules can attach. The adjustable pore structures in zeolites refer to the ability to control the size and shape of the zeolites pores. This can be done by changing their chemical composition. Thus, allowing zeolites to target and trap only specific molecules. A zeolite's chemical stability is significantly important as it has the ability to perform under harsh conditions, such as high temperatures. The stability that they provide makes them reliable for repeated use in industrial processes. The one disadvantage is some zeolites can be affected by moisture.

On another level, metal-modified zeolites have emerged as a promising class of materials for CO_2 capture due to their enhanced adsorption capacities and selectivity properties. These materials incorporate metal ions within the zeolitic framework. This consists of a continuous network of silicon (Si), aluminium (Al), and oxygen (O) atoms that are linked together to form a solid structure. The zeolitic framework is what determines the size and shape of those pores. This is important as the pore size controls the gases that can enter and be trapped. Thus, significantly altering their physicochemical properties. For metal modified zeolites, this means that the metal ions create charged sites in the zeolite. Thereby, causing a stronger electrostatic attraction between the CO_2 and zeolites, and improving their iattraction with CO_2 molecules (Ganiyu 2025).

Zeolites are silicates consisting of tetrahedral SiO4 units. The materials are made of repeating silicon-oxygen units which are arranged in a 3D structure with tiny pores. They can trap gases, such as CO_2, that are connected through o-bridges. This generates three-dimensional crystalline microporous structures (that means with pores with d < 2 nm). There are various types of zeolite structures that exist and they can be distinguished by their size and shape, These include Zeolite 13X, Zeolite 5A and Zeolite NaY. In zeolite structures, a fraction of the si atoms can be interchanged with other elements. For instance, Aluminum (AI) being the most common substituent. Therefore, zeolites can be classified as aluminosilicates. The presence of Al (oxidation state +3) instead of Si (+4) yields a negatively charged (Boer et al., 2023).

The two most commonly proposed adsorption mechanisms in medium and large pore zeolites include the interaction of one of the oxygen atoms of CO_2 with an extra-framework cation of the zeolite. In addition, a bridging mechanism where both oxygens of CO_2 interact with different extra-framework cations of the zeolite. A less commonly observed mechanism involves the formation of a carbonate or a carbonate precursor. Here, one oxygen of CO_2 interacts with the cation site. Whilst the carbon of the CO_2 molecule interacts with oxygen of the zeolite framework. This defines many significant characteristics of the material, such as the number of T atoms (T = Si or Al) in the rings and the related pore size (Å). The pore aperture should be at least 3.3 Å in order to allow CO_2 to diffuse through. Whereas, the apertures of smaller rings are too narrow. The pore size can be adjusted by incorporation of alkali and alkaline earth metals, which can in turn affect the adsorption mechanism. Another property that is related to the zeolite framework is the surface area. Zeolites with the same structure and similar crystal size should in principle have a similar surface area (Boer et al. 2023).

2.1.3 Need for an Alternative Method

Both zeolite-based adsorption and amine-based absorption are effective CO_2 capture methods. however, each has limitations related to energy demand, stability, and scalability.

Amines

It is important to note that device efficiency can usually deteriorate with time. This is primarily due to the build-up of pollutants and impurities and lack of maintenance. A single method cannot be selected based only on the solution flow rate when employing amine-based compounds as chemical solvents. Consequently, it is essential to point out the typical characteristics of conventional amines.

Low Carbon Dioxide Loading Capacity: determining the effectiveness of absorption depends on the solubility of CO_2 in the liquid phase. Therefore, the physical solubility of CO_2 in solutions can also be increased by substituting organic co-solvents such alcohols for water in amine solvents. However, a disadvantage for industrial applications is the high volatility of co-solvents. Additionally, the effectiveness of heat exchangers, absorption kinetics and pumping costs may be negatively impacted by the increased viscosity of organic solvents, such as amines.

High Corrosion Rate of the Equipment: CO_2 capture systems as amine-based chemical solvents are used in industrial processes. This may corrode lines and equipment owing to their chemical nature. Thus, leading to bicarbonate and carbamate species. Some techniques have been implemented, such as incorporating corrosion inhibitors or introducing alternate absorption liquids. Electrochemical tests must be performed to clarify the potential harm incurred by the preceding evidence. Other operational problems can include solvent chemical instability, which refers to the tendency of a solvent to break down or decompose. Amine oxidation occurs by SO_2, NO_2, HCl and HF, and the presence of oxygen in the natural gas stream. Oxidative degradation of amine solutions reduces CO_2 capacity absorption and can increase corrosion in natural gas treatment facilities.

High Energy Consumption: Using an alkanolamine, such as a liquid absorbent, can cause variable debris and operative problems. This includes volatility, corrosion and thermal degradation at 100 to 150◦C. Thus, making it difficult to control. Therefore, the use of power and cost is high and may increase in each absorption process. This means that developing improved chemical methods for CO_2 capture processes is required to prevent high temperatures and mitigate their adverse effects.

Toxicity and Environmental Issues: An important issue with the industrialisation of the amine-based CO_2 capture technology is solvent emissions. Thermal and oxidative stressors can cause amine-based solvents to degrade during operation. Therefore, producing toxic byproducts, such as nitrosamines, nitramines and aldehydes that can endanger ecosystems and human health. In many jurisdictions, nitrosamines in particular are subject to stringent regulations and are considered possible carcinogens. Furthermore, improper management of amines and their breakdown products can cause contamination and environmental damage by leaking into water systems. Amine solutions' corrosive properties also raise maintenance and material costs, which may make waste management problems worse because corroded materials need to be disposed of (Loachamin et al., 2024).

Zeolites

According to research, although there have been many significant improvements that are made when working with zeolites, there are various challenges that should be tackled to maximise the potential of the zeolite-based CO_2 capture systems in the real world. These include Moisture Sensitivity. This means that the uptake of CO_2 is lowered in the presence of water vapor which is a common constituent in flue gas in a large number of zeolites. The construction of hydrophobic or water-tolerant structures of zeolites is an urgent requirement.

Limited Selectivity: Despite the fact that some of the frameworks demonstrate plausible CO_2 /N_2 selectivity, it still needs further improvement. This is particularly at low partial pressures of CO_2, as it would occur in post-combustion situations.

Energy-Intensive Regeneration: Zeolites can usually be regenerated using less energy than liquid solvents. In saying that, overall energy usage can be reduced by enhancing the thermal desorption of the zeolites.

Cyclic Stability: Stability over a series of adsorption or desorption cycles. This includes especially those in harsh flue gases. This is also one of the challenges that should be carefully considered.

Cost and Scalability: The financial viability of the synthesis of functionalised or modified zeolites in large scale needs to be optimised further.

2.2 Understanding MOFs in Carbon Capture

Metal-organic frameworks (MOFs) are a new class of crystalline porous hybrid materials whose structure, porosity and functionality can be precisely tuned. They are well-positioned for applications in energy storage, gas separation, environmental remediation and catalysis. This is due to their large surface area, carefully designed pore structures and variety of synthesis techniques. For instance, hydrothermal, microwave, electrochemical and mechanochemical methods. These methods refer to different ways of forming MOFs by combining metal ions and organic linkers under controlled conditions.Hydrothermal synthesis is the process of heating reactants in water at high temperature and pressure to form crystals. Microwave synthesis heats the mixture rapidly using microwave radiation, accelerating MOF formation. Electrochemical synthesis uses an electric current to create metal ions which react with organic linkers. Mechanochemical synthesis involves grinding the reactants together, often in the absence of solvents, and is faster and environmentally friendly.

Metal-organic frameworks (MOFs) have advanced rapidly in recent years, increasing their efficacy and sparking interest in the sector. MOFs come in a wide variety of sizes and forms. Organic ligands and inorganic building units, such as clusters, bind them together. This diversity results from the wide range of cluster and linker species, as well as the particular coordination bond orientations, adjustable porosities and customisable capabilities that make them extremely adaptable for a number of uses (Zeggai et al. 2025). MOFs are well known for their large surface area. For instance, 1g of a metal organic framework is said to have a surface area of around 7800m^2. This is comparable to the size of one and a half football fields. This makes MOF's carbon capture a much more feasible option compared to other traditional methods for carbon sequestration and gas separation. The highest recorded MOF DUT-60 (1 gram) had a surface area of 7800m^2.

New MOFs with distinct crystal structures, high surface area, particle size, pore size distribution and morphologies have been produced during the last 20 years using a variety of synthetic techniques. Thus, giving researchers a special platform to alter desired features. One synthesis method for creating MOF single crystals is the hydrothermal approach, which combines metal salts with organic ligands in a water media. This process is known as a hydrothermal approach because it uses water as a solvent. It has been used to create high-performance MOFs and their composites with regulated size and structure, and its benefits are straightforward and safe.

In the early days, MOFs played a key role in the field of gas adsorption and storage, realising gas separation by adjusting the pore structure. On the other hand, MOF application fields have grown significantly in recent years. Many MOFs have demonstrated their potential in a variety of applications, including drug delivery, biosensing, energy harvesting, energy conversion and catalysis. MOFs are employed as drug release carriers. Thereby offering a novel approach to accurate drug delivery. MOFs are employed in biosensing to support biomedical research and diagnostics through molecular detection, protein analysis and cell imaging. Furthermore, MOFs are being used in optoelectronics, energy and for the environment. Its adaptability and tunability have spurred advancements in scientific study and real-world applications, showcasing MOFs' growing potential in multidisciplinary research and innovation and continuously boosting the energy, environmental protection and healthcare sectors (Li et al., 2024). Although Gas separation has been the main focus, it has not reached its potential due to the novelty of MOFs.

2.2.2 History of MOFs

Researchers, such as Professor. O. M. Yaghi's groundbreaking work in the 1990s proved that mixing metal salts with organic linkers might produce highly porous and crystalline structures with large surface areas and adjustable characteristics.The synthesis of coordination polymers gave rise to the early ideas of MOFs, which have their origins in coordination Chemistry. It began in the late 20th century. The creation of MOFs represents an amazing journey in the realm of porous Science. Due to their distinct pore characteristics, this invention gave rise to a new class of materials with substantial potential for a wide range of uses. MOF research advanced quickly in the ensuing decades due to advances in computer modeling and synthesis approaches. These developments made it possible to precisely construct and functionalise MOFs, greatly expanding their range of applications. As MOFs' pore size, shape, and functionality can be customised, they are being investigated in a variety of domains, such as medicine delivery, energy storage and environmental cleanup (Han et al., 2025)

2.2.3 MOFs in Carbon Capture

Metal-organic frameworks (MOFs) trap carbon dioxide by adsorption. This means the attachment of CO_2 molecules to the surface of the material. MOFs consist of metal ions which are linked together by organic linkers, and they consist of highly porous, three-dimensional structures which have a very large internal surface area. Passing through MOF, CO_2 molecules enter the small pores and react to the internal surfaces. Such interactions may be either physical. For instance, . weak van der Waals forces. As an alternative, they could bechemical, when the MOF has been functionalised with functional groups, such as amines that strongly interact with CO_2 . Due to the ability to design MOFs with desired pore sizes and chemical characteristics, they can capture CO_2 selectively even at extremely low concentrations, including those in the atmosphere. After the CO_2 has been captured by the MOF, the material can be reused by increasing or decreasing the temperature or pressure to release the capturedCO_2 . The combination of high surface area, tunable structure and efficient regeneration makes MOFs a novel promising material in carbon capture applications.

Currently taken as the benchmark in CO2 adsorption regarding MOF materials, MOF-74-Mg, is known for its high CO_2 uptake in dry conditions and its remarkable selectivity. Extensive studies have demonstrated that the dominant interaction mechanism between CO2 molecules and MOF-74-Mg is through an open Mg2+ site (Maia et al., 2021).

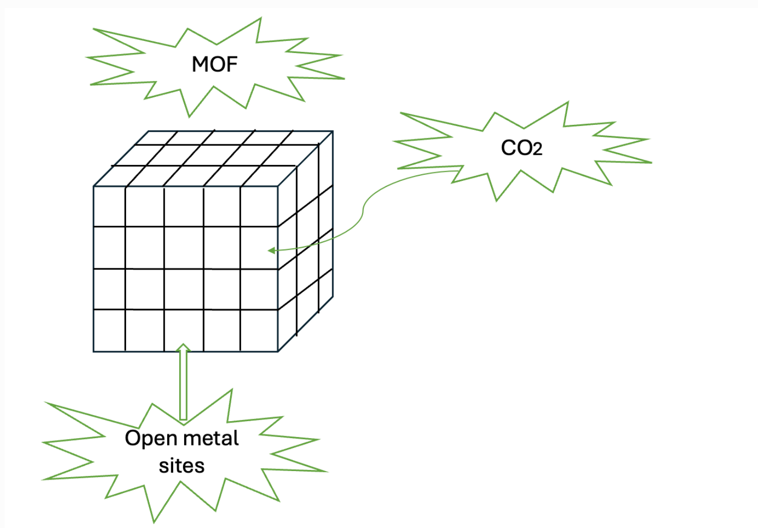

Figure 4: A diagram showing how CO_2 can be adsorbed by the open metal sites in the metal organic framework

Types of MOFs and their Role in Carbon Capture

There are various different types of MOFs. However, only some are specific to carbon capture. A few of the most prominent ones include MOFs MOF-74-Mg, HKUST-1, SIFSIX-3-Mand ZIF-8. These MOFs were chosen due to their diverse structural architectures towards CO_2 capture. They have open metal sites, ultra-microporosity and a flexible framework. These arefeatures which are present in the majority of MOFs used for this application (Maia et al. 2021).

Efficiency

Different MOFs have different efficiencies. This is due to the fact that there are many variations of MOFs, and each of them can serve a different purpose. MOFs under various conditions, such as humidity and temperature, are crucial for effectiveness in practical applications. A novel Zn-based three-dimensional framework, Zn(Py)(Atz), demonstrated outstanding stability and performance, with a surface area of 764.5 $m^2.g^{-1}$ and a pore volume of 0.32 $cm^3.g^{-1}$. It exhibited a CO_2 adsorption capacity of 52.3 $cm^3.g^{-1}$ at 273 K and achieved a 92.1% propylene carbonate yield with 98% selectivity under mild conditions (60°C, 1.5 MPa). Zn(Py)(Atz) maintained excellent stability in water and in acidic and basic solutions (pH 2–14 for 72 hours) and could be recycled seven times with minimal loss in efficiency (Lan et al., 2020). This essentially showcases one type of zinc based metal organic framework in which the material can hold 52.3 cm^3 of CO_2 gas per gram. This is just one example of MOF that has a good efficiency. There are several others that also exist, such as MOFs MOF-74-Mg, HKUST-1, SIFSIX-3-M and ZIF-8.

Applications

MOFs have several applications and can be used for several things. This paper focuses mainly on storage of gases, such as hydrogen and carbon dioxide. Other possible applications of MOFs are in gas purification, gas separation, water remediation, catalysis and as supercapacitors. MOFs can be effectively used in gas separation. This is due to the highly porous nature. The results can vary from different types of MOFs. The structured UiO-66 achieves a cost of $72.50 per ton of CO_2 captured with 95% purity and 88.8% recovery, which decreases to $60.60 per ton with 80% recovery,. Structured ZIF-8 costs $80.20 per ton with 91.2% purity and 74.4% recovery.Structured MIL-101@GO costs $75.00 per ton for 96.4% purity and 88.6% recovery. In order to evaluate the viability of structured adsorbents for commercial-scale CO_2 capture, this study emphasises the significance of using cost as the primary evaluation metric, integrating data, and optimising adsorption processes with precise equipment (Gebremariam et al., 2025). This showcases that MOFs are to a great extent cost effective and energy efficient. When comparing Metal-Organic Frameworks (MOFs) to traditional amine scrubbing and zeolites, MOFs can offer a superior balance of efficiency and lower energy costs.

Drawbacks and Open Questions

MOFs and other solid sorbents are promising options for low temperature carbon capture. It is possible to tailor MOFs for better CO_2 uptake capacity and selectivity. This is due to to their inherent qualities, such as their high porosity and chemistry. It is important to note that MOF sorbents have a number of drawbacks. It is widely acknowledged that the cost and cycle time of the C-capture operation and regeneration process are influenced by the thermal conductivity and moisture. However, MOFs can exhibit low thermal conductivities. Currently, there are very few studies which have been conducted on the improvement of MOF's thermal conductivity. Therefore, additional research is necessary in this area. On another level, the majority of MOFs cannot currently be produced on a large scale. For MOFs to be included in the Carbon capture process, they must be structured sorbents. Therefore, finding methods to convert MOFs into pellets, beads, fibers, or monoliths is essential.

Nowadays, solvothermal batch techniques are commonly used to synthesise MOF powders. These procedures can take a long time. They involve complicated purification techniques, and can utilise pricey organic solvents. These issues result in high production costs, which could make them less appealing from an economic perspective. Recent advancements include the utilisation of twin-screw extrusion (TSE) kilogram per hour-scale MOF synthesis without the use of ore-reduced solvents. In saying that, there is still more work to be done on the efficient and cost effective utilisation of MOFs in carbon capture.

In addition to the mentioned issues, a number of factors, such as toxicity, life-cycle assessment studies and economic ramifications, must be taken into account when proposing uses for newly developed materials. However, a significant disadvantage that has limited the use of MOFs in this field is their stability under CCS operating conditions. Many MOFs have low hydrolytic stability. This implies that MOFs are likely to break down when they come into contact with moisture. There have been advancements in the industry to deal with this problem, and current studies indicate that things could become better. Doping MOFs with alkyl amines (or other chemical functionalities) and enhancing the MOF's hydrophobicity are the two ways which are under under investigation (Sher et al.,2024).

METHODOLOGY

Details about the Websites that Were Used

The peer-reviewed scientific literature from databases and academic publishers, such as the Royal Society of Chemistry, ScienceDirect, SpringerLink and ResearchGate, were used There were approximately 15 studies used from 2020 to 2026. The studies chosen were for CO_2 capture with metal-organic frameworks (MOFs), zeolites, and amine-based absorption systems.. Furthermore, they provided important information that linked to the structure, porosity and feasibility for carbon capture. These websites enabled the comparison between the current and traditional methods that were used for carbon capture and allowed the research to identify the future scope of MOFs in carbon capture.

Keywords that were Used

A variety of keywords were used, such as metal-organic frameworks (MOFs), porous materials, high surface area, tunable pore structure, CO_2 adsorption, CO_2 capture, direct air capture (DAC), gas separation, CO_2 selectivity, adsorption capacity, temperature swing adsorption (TSA), pressure swing adsorption (PSA), amine scrubbing, chemical absorption, zeolites, microporous materials, adsorption/desorption, post-combustion capture, greenhouse gas removal, and percentage yield.

Inclusion Criteria

The inclusion criteria for this study focused on selecting reliable peer-reviewed sources that are directly connected to CO_2 capture. This includes papers that have provided information about metal-organic frameworks (MOFs), amine scrubbing and zeolites. Moreover, priority was given to studies that included quantitative data, such as adsorption capacity, selectivity and regeneration conditions. This enabled for clearer comparison between the different methods. Sources that considered real-world conditions, such as temperature and humidity, were also considered to ensure that the findings were relevant.

Exclusion Criteria

Studies which had nothing to do with CO_2 capture or gas separation were eliminated as they had no relevance to the paper. Research papers without quantitative information about adsorption capacity, selectivity and percentage yield were disqualified as they could not be used for comparison purposes. Furthermore, as they were outside the scope of this research, sources that did not involve MOFs, zeolites or amine-based systems were excluded, as they were theoretical studies without conclusive experimental and/or modeling results.

Strengths of the Methodology

A key strength of the methodology is that it introduces a wide variety of research studies and perspectives. Therefore, allowing for a broader and more comprehensive understanding of carbon capture technologies. By analysing multiple sources that focus on metal-organic frameworks (MOFs), amine scrubbing and zeolites, the study is able to compare different approaches by using existing experimental and modelling data. In addition, the inclusion of quantitative information, such as adsorption capacity and selectivity, strengthens the reliability of the comparisons and supports more evidence-based conclusions.

Limitations of the Methodology

A major limitation of the methodology is that it relies entirely on secondary data. Thus, the research has been conducted by other authors. This raises questions about how much the results can be fully relied upon, as the accuracy depends on the validity of the original studies. Additionally, differences in experimental setups, assumptionsand conditions across the sources can make direct comparisons less consistent. Since many studies are carried out under controlled or simulated conditions, the findings may not fully reflect real-world performance. This is applicable particularly for newer technologies, such as MOFs.

1. A review on metal-organic framework: synthesis, properties and application, Characterization and Application of Nanomaterials (2019). Published by EnPress and written by Soni et al., (2018)

The paper has discussed the synthesis, properties and the different applications of MOFs. The literature review includes the structure and factors that are affecting the stability of MOFs, such as temperature and PH. Furthermore, the study has focused on gas separation and storage which explores MOFs, and how their structure and surface area can reduce atmospheric CO_2 . The findings have demonstrated that MOFs have a large surface area. This allows them to adsorb large amounts of CO_2 with small amounts of MOF. The findings of the research paper reported that MOF-210 has an exceptionally high surface area of 10,450 m² and that higher synthesis temperatures can improve crystal quality and thermal stability. The study showcases a strong set of findings on the structure and synthesis of MOFs. However, it does not fully explore the utilisation with CO_2 and does not compare with other traditional methods for Gas absorption and adsoption. The paper stated that MOFs would be good for gas adsorption. The limitation of the study is that it does not say how effective it is when compared to other methods for adsorbing atmospheric CO_2 .

2. Application of metal-organic frameworks for CO_2 capture, Highlights in Science, Engineering and Technology (2024). Published by DR Press and written by Zhao, (2024)

The paper has analysed the application of metal organic frameworks for CO_2capture. It has highlighted its structure, its ability for CO_2/N_2 selectivity and compared it with traditional methods for carbon capture, such as Zeolites. The findings of the paper have indicated that metal-organic frameworks, in particular CALF-20, have great potential for CO_2 capture because of their high CO_2/N_2 selectivity, high adsorption capacity, durability and better performance in humid environments when compared to conventional adsorbents, such as zeolite 13X. According to the study, zeolite 13X performs poorly in wet conditions, while CALF-20 retains CO_2 capacity at up to 40% relative humidity. Thus, indicating a significant benefit for practical uses. The advantage of this paper is that it has explored MOFs and compared them to a traditional method for CO_2 capture, such as Zeolites.

3. Advanced metal–organic framework materials for efficient CO_2/CH_4 separation using pressure swing adsorption – numerical study, Adsorption (2026). Published by Springer and written by Mohamed et al., (2026).

The paper has identified the structure, large surface area and capacity of MOFs to selectively adsorb CO_2 over other gases, such as CH_4. Additionally, it simulates pressure swing adsorption (PSA) and assesses performance under various operating situations by using a numerical modeling approach. According to the findings, MOFs have a considerable potential for effective gas separation and a high CO_2 selectivity. Nevertheless, the study does not offer a thorough comparison with conventional carbon capture techniques, such as amine scrubbing. Furthermore, it primarily depends on models rather than practical application of MOFs.

4. Development of the design and synthesis of metal–organic frameworks (MOFs) – from large scale attempts, functional oriented modifications, to artificial intelligence (AI) predictions, Chemical Society Reviews (2025). Published by the Royal Society of Chemistry and written by Han et al., (2025).

The paper has examined MOFs by focusing on their design and structure. It has evaluated how AI can be incorporated with MOFs. In addition, It has highlighted how functional modifications and advancements in synthesis methods can improve properties, such as surface area, stability and adsorption performance. The study has explored the use of artificial intelligence (AI) to predict and optimise MOF structures for applications, such as gas storage and CO_2 capture. According to the results, MOFs have great potential because of their tunability and developing synthesis methods. Nevertheless, the paper does not examine traditional methods and it primarily concentrates on research and design rather than direct performance comparison. It does not thoroughly assess MOFs against conventional carbon capture techniques on a large industrial scale.

FINDINGS AND DISCUSSION

The Significance and Limitations of MOFs

Technology	Capture mechanism	Advantages	Disadvantages	Energy demand	Moisture sensitivity	Cost/scalability
Amine scrubbing	**Chemical absorption**	**High CO_2 selectivity, established technology, high capture efficiency**	**Corrosion, solvent degradation, toxic by-products**	**High due to regeneration**	**Low-medium**	**High infrastructure but expensive operation**
Zeolites	**Physical adsorption in porous structures**	**Stable,reusable, low regeneration energy**	**Lower selectivity, affected by humidity**	**Medium**	**High in some types**	**More scalable than MOFs**
MOFs	**Tunable adsorption**	**Very high surface area, adjustable**	**Cost, stability, scale-up**	**low**	**Depends on structure**	**Affordable and has potential**

	through porous frameworks	**pores, high selectivity**	**challenges**			**for future scalability**

This research article discusses how metal-organic frameworks (MOFs) are promising materials for carbon capture because of their relevant CO_2 selectivity, customisable pore structures and enormous surface area. This paper has demonstrated that MOFs can attain large adsorption capacities and can be altered to improve their performance. This can be achieved by functionalising them with amine groups or adding unsaturated metal sites. In contrast, conventional techniques, such as zeolites and amine scrubbing are efficient.
The study has documented that MOFs are an appropriate substitute for the common traditional methods. In saying that, it has some limitations. This is due to the fact that some MOFs might have problems with moisture. Similarly, amine scrubbing is illustrated to be highly efficient in capturing CO_2 and is widely used at industrial scale. However, it requires large amounts of energy for solvent regeneration. Therefore, making it less energy-efficient overall. On another level, Zeolites are effective solid adsorbents due to their porous structures. However, their performance decreases in humid conditions because water molecules compete with CO_2 for adsorption sites. Overall, the research has stressed that while traditional methods are currently more established, MOFs can offer improved flexibility and performance potential for future carbon capture applications.

Furthermore, the research paper has pinpointed that the efficiency of carbon dioxide capture methods is greatly affected by the structure, chemistry and conditions of the materials which have been used. The key advantage of MOFs is that they can be tailored on the molecular level to control pore structure, surface chemistry and adsorption properties. This enables them to effectively capture CO_2 even at low concentrations. Thereby, making them ideal for direct air capture. By comparison, amine scrubbing is based on chemical absorption, which is highly efficient but it is energy-intensive. Zeolites rely on physical adsorption in rigid pores.

Studies have indicated that MOFs offer a more adaptable and potentially more environmentally friendly approach to carbon capture. This paper has indicated that they have lower energy requirements compared to traditional amine based solvents. There are a number of key differences in performance. For instance, for MOFs, structural and functionalisation variations affect the CO_2 binding and selectivity. MOFs, such as MOF-74-Mg and Zn(Py)(Atz),are highly efficient because of the presence of open metal sites and advantageous pore structures, In addition, other factors including temperature and humidity are important as they may have an effect on the efficiency of the MOF.

It is important to note that some MOFs are stable in humid environments. However,others can break down. Thus, presenting a challenge for their practical use. On the other hand, Zeolites can perform well in dry conditions. However, they are less efficient in humid conditions. Amine scrubbing efficiency can be affected by the type of solvent - with monoethanolamine (MEA) being the most common because of its high capacity. These differences demonstrate that performance is sensitive to material design and operating conditions.

It is important to note that there are correlations among the studies. One observation for that is that materials with larger surface area tend to have greater CO_2 adsorption capacity, which accounts for the excellent performance of MOFs. Another trend is that material functionalisation enhances CO_2 selectivity. In saying that, it might increase regeneration energy. This presents a balance between efficiency and energy use, as witnessed in amine scrubbing. The approaches taken in the studies reviewed, such as experimental testing and mathematical modelling (for example, pressure swing adsorption simulations) can illustrate how structure and chemistry can affect performance. These methods offer insight into designing MOFs for enhanced carbon capture performance.

The research has pinpointed that MOFs, amine scrubbing and zeolites have distinct characteristics. MOFs can be tailored for particular uses. However, zeolites have rigid structures and are less stable under varying environmental conditions, particularly humidity. Amine scrubbing is distinct due to its liquid chemical solvent, which has high efficiency, high energy usage and potential environmental risks from solvent degradation. This makes traditional methods currently more familiar and commonly employed. However, MOFs represent a more adaptable and potentially environmentally friendly approach. Their practical applications are currently under investigation.

Lastly, MOFs have some disadvantages that can hinder commercialisation. This includes their cost, poor thermal conductivity and instability. This is especially in moist conditions, where some MOFs may break down. Moreover, many reports are limited to laboratory-scale experiments and modelling, which may not translate to real-world applications. Thereby, resulting in a disconnect between theoretical potential and practical application. Furthermore, amine scrubbing has issues with energy consumption, equipment corrosion and potential toxicity of by-products. Although Zeolites are more stable and sensitive to water, they can have low selectivity in some situations.

CONCLUSION

This study has assessed the efficiency of traditional carbon capture technologies, such as amine scrubbing and zeolites versus metal-organic frameworks (MOFs). The research has demonstrated that although conventional processes are effective and well-established, they are constrained by energy-intensive processes, environmental issues and low selectivity in some cases. On the other hand, MOFs have a large surface area, are highly customisable and have selective CO_2 binding. Therefore, indicating that they represent a more efficient and flexible solution to carbon capture.

The results indicate that MOFs could increase the efficiency and sustainability of technologies for removing CO_2. However, there are still issues to be resolved in regards to cost, scale-up and stability. All in all, according to research, MOFs are promising next generation candidates, but their commercial use depends on improvements in stability, cost, shaping into pellets or monoliths, and large scale testing. This is significant as environmental industries and governments could fund the development and trialling of MOF-based systems in order to support measures to mitigate issues, such as climate change.

Future studies should aim to optimise the stability of MOFs under real-world conditions, lower the cost of producing MOFsand explore large-scale applications. Other potential research could investigate combined MOF and traditional approaches and new applications, such as CO_2 valorisation.This refers to the processing of capturing CO_2 emissions and converting them into usable products rather than storing them as waste,These products could include fuels, construction materials and polymers. One avenue of research could look into how MOFs can be tailored for industrial applications while being efficient and cost-effective.

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