Automated Eco-Friendly and Cost-Efficient CO_2 Capture System: a Novel Zeolite-MOF Hybrid Material

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INTRODUCTION

In the last few years, increasing CO_2 levels in the atmosphere have become one of the biggest problems the earth is facing (FIG.1.). Not only causing global warming, which critically affects the world, but also affecting human health significantly [1]. When humans are exposed to high amounts of CO_2 emissions it can lead to high levels of CO_2 in the blood, which is linked with the decrease in pH levels of the blood resulting in a condition known as acidosis. Acidosis affects the respiratory, cardiovascular, and central nervous systems of humans remarkably, producing various symptoms such as headache and dizziness. These symptoms happen with short-term exposure to CO_2, but if the exposure is high, the symptoms could lead to fatigue, coughing, and irritation of mucous membranes [2] .

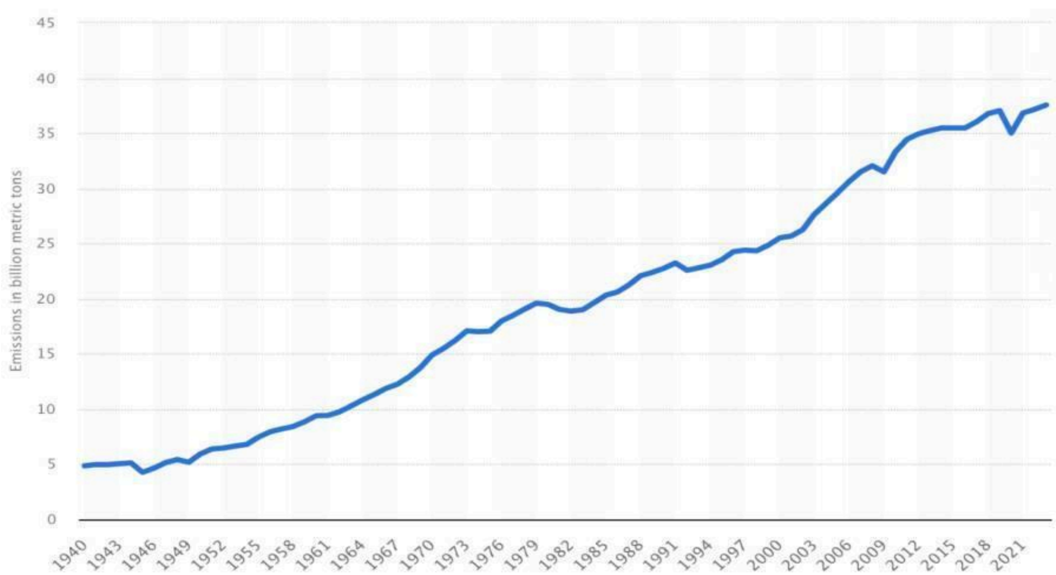


FIG.1. Shows CO_2 Emissions Over The past 80 Years [3]

Studies have also shown that the levels of CO_2 in 20–50% of classrooms normally exceed 1,000 ppm (particles per million) and are often much higher, sometimes reaching levels as high as 6000 ppm for extended periods. According to research by P. Bierwirth (2024), CO_2 concentrations above 1000 ppm are linked to decreased student and instructor attendance, a lack of focus during class, and most of the symptoms listed above. While continuous CO_2 emissions adversely affect human health, marine life is also paying the price. The exposure of marine life to continued CO_2 is harmful to both marine food webs and ecosystem functions, which are both critical parts of the survival of aquatic life [4].

Unarguably, ocean acidification poses a main threat to marine life. It happens when carbon dioxide dissolves in the ocean and reacts with its water, generating carbonic acid. H+ ions and inorganic carbon species are released when this acid dissociates. Raises in CO_2 lead to an increase in H+ concentration which lowers pH and raises acidity which lead to a big impact on the seawater carbonate system [5].

About 30% of CO_2 emissions released into the atmosphere are absorbed by the ocean. The pH of the oceans surface water has dropped from 8.2 to 8.1. This means that the oceans are almost 30 percent more acidic than in pre-industrial times. Studies, however, indicate that by the end of the twenty-first century, the partial pressure of CO_2 may cause the pH of the ocean to further decrease to about 7.8, resulting in 150 percent more acidity, which can result in the rise of global temperatures by about 2 °C on average during the next century [6].

Most importantly, the cause of these crucial problems needs to be addressed to help stop the problem. The atmospheric CO_2 concentration is largely caused by the combustion of fossil fuels for energy generation, deforestation, and agricultural practices, which are also important for human living and evolution [7].

Additionally, the Industrial Revolution increased CO_2 levels massively in the atmosphere. This CO_2 was emitted after the usage of fossil fuels for energy. The issue got worse because of the increase in industrial production. Hence, this led to massive forest destruction. As a result, these emissions have caused the ongoing problems associated with climate change. This also causes global warming by continuously raising atmospheric CO_2 concentrations. Therefore, the Industrial Revolution's impact on atmospheric CO_2 concentration levels and its long-term consequences on the Earth's climate are well evidenced, however, some current attempts and methods are being implemented to help stop the crisis.

One of the main aims of contributing to the stop of increasing CO_2 levels in the atmosphere and the oceans are the SDG’s goals. More specifically, goal 13 focuses on climate action and the importance of acting instantly to the change of the climate to reduce the consequences in the near future. However, goal 14 is more focused on seawater and its clarity and health, which links back to ocean acidification and its causes.

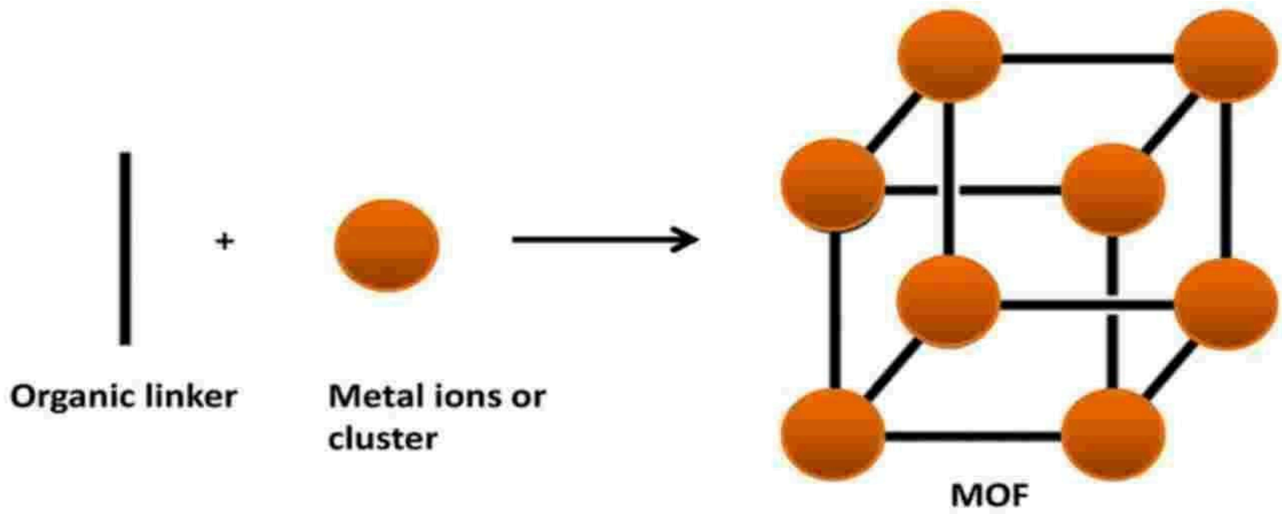
SCIENTIFIC BACKGROUND

Developing materials and techniques for adsorbing CO_2 is the best way to improve air quality and reduce climate change for now and the future, that is why many scientists did their research on CO_2 capturing materials. Zeolites, metal-organic frameworks (MOFs) and amine solutions stand out the most due to their high capture capabilities, low costs and efficient regeneration among their alternatives for CO_2 capture.

Amine solutions are commonly used in power plants and natural gas processing facilities. On the other hand, MOFs draw more interest in research due to their high tunability and exceptional surface areas that help with the efficiency of CO_2 capturing [8]. Zeolites, remarkably, are useful in industrial and environmental atmospheres due to their excellent thermal stability and resistance [9]. However, improving CO_2 capture technology needs an understanding of the positive aspects and downsides of these materials.

For Amine Solutions, it is known for its high selectivity and capture capabilities due to the good porosity [10]. However, it is mostly used for its low cost due to the many facilities which already have amine based technologies. This means that many industrial applications and researches have been done thus creating cost effective technologies. Yet, Amine solutions have the potential to be extremely corrosive when saturated which creates a serious risk to the environment and could raise maintenance expenses [11]. In addition, it consumes a lot of energy from the power plant's energy output in its regeneration process being extremely inefficient [12].

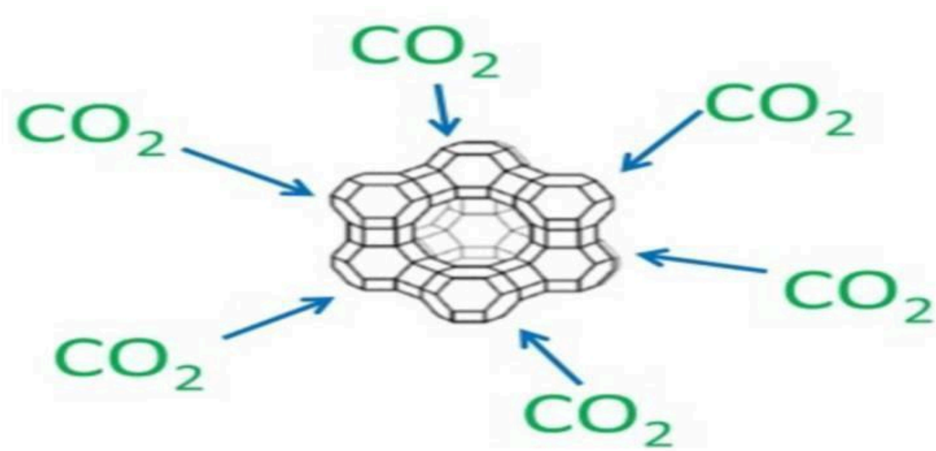
On the other hand, Metal-Organic Frameworks (MOFs) have even higher CO_2 capture abilities due to its extraordinarily large surface area which can range from 1500 to 7000 m^2/g [13]. Moreover, its tunable properties - using different metal ions and organic linkers (Look at Scheme 1) - improves its ability to capture CO_2 in different conditions and environments which is what is needed for application purposes [14]. Also, MOFs are way more energy efficient than other materials because they usually require lower temperatures for capture and regeneration [15].



Scheme 1: A General 3-D structure of MOFs

However, the cost of producing MOFs is higher than Zeolites and amine solutions but it is predicted that costs will go down as soon as production techniques advance. In addition, most MOFs have low stability in humid conditions which could have an impact on their performance [14].

Moreover, Zeolites are known for their high strength and durability making them suitable for various environmental and hydrothermal conditions including humid ones unlike other materials [16] (Look at Scheme 2). They can also capture CO_2 well, but its surface area limits its performance compared to MOF's. It also requires higher temperatures for regeneration, which can increase the overall costs.



Scheme 2: General representative of CO_2 capture by Zeolites

OBJECTIVES

Hypothesis: The hybrid material that has been synthesized would have higher CO_2 adsorption capacities than MOF-808 and Zeolite alone. Furthermore, it is expected that the hybrid material will show improved efficiency alongside stability over multiple reuses with lower costs of synthesis.

Novelty: The new material will perform better without being overly costly thanks to the hybrid's natural zeolite which has much reduced cost due to its abundance in Saudi Arabia and stronger adsorption capabilities due to the high surface area of the MOF-808. Furthermore, the material uses less energy throughout regeneration cycles making it even more reliable.

Purpose: This project aims to protect the environment, including the land, the oceans, and wildlife, as well as people worldwide in order to achieve a green future. The invention aims to reduce the harm caused by rising CO_2 levels and promote sustainability and harmony between humans and nature in order to build a healthier and more environmentally friendly future. By improving the foundation for more effective CO_2 capture and storage technologies, this research will significantly contribute to the plans of SDG 13 which links to climate action and SDG 14 which aims to reduce the effects of climate change on the oceans and the world. The research can also help in achieving the Saudi Arabian net zero emissions goal by 2060.
In addition, this project aims to empower factories and cargo ships to increase production and revenue by eliminating taxes and limits on CO_2 emissions. It also aims to help governments and world associations monitor emissions to maintain progress and change.

METHODOLOGY

To tackle the critical issue of CO_2 emissions, we developed the Marine Transportation Units System for CO_2 Capture (M.T.U.S.C.C) alongside a new hybrid material designed to capture CO_2. Not only does the system offer a sustainable and efficient solution to minimize the emissions, but it is fully automated. Moreover, it utilizes abundant resources found to cut down costs while maintaining performance. There are two main inventions associated with this technology, the material and the system

Material

This project will follow a regulated hydrothermal method to synthesize the hybrid material. The goal is to accurately blend MOF-808 with Zeolite to optimize the combined benefits for improved CO_2 storage and capture capacities. The idea is to produce a well-defined, cost-efficient and stable hybrid structure that can effectively adsorb CO_2 molecules by carefully monitoring the hydrothermal process.

The study will be carried out with scanning electron microscopy (SEM) and X-ray diffraction (XRD). The structure of the hybrid material will become clear through the analysis of XRD data. SEM technique will also provide an in-depth visual analysis of the particle size distribution and surface form, which will help understand the hybrid material's physical properties at a microscale level.

The thermal stability of the material under various temperatures will be examined by thermogravimetric analysis (TGA) which will help with gathering information regarding the material's temperature response and suitability for CO_2 capture applications. Additionally, the adsorption and desorption kinetics of CO_2 on the hybrid material will be evaluated, as well as the material's durability and efficiency throughout several operational cycles, through High-Pressure Volumetric Analyzer (HPVA) examinations.

Procedure:

Synthesis of MOF-808:

- Prepare a solution containing trimesic acid (benzene-1,3,5-tricarboxylic acid, H_3BTC) zirconium oxychloride octahydrate ($ZrOCl_2 \cdot 8H_2O$) and a mixture of N,N-dimethylformamide (DMF) formic acid and deionized water.
- Then stir the solution carefully until it's fully dissolved. Transfer it to an autoclave.
- Place the autoclave in a preheated oven at 120°C for 24 hours to initiate the hydrothermal reaction.
- After cooling to room temperature, filter the precipitate and wash thoroughly with DMF and methanol to remove any unreacted materials.
- Dry the obtained MOF-808 in a vacuum oven at 80°C for 12 hours.

Preparing of Zeolite :

- Grind the natural Zeolite to make small particles less than 125 micron.
- Filter and wash the Zeolite with deionized water until the pH is neutral.
- Dry the Zeolite at 100°C for 12 hours.

Hybrid Material Synthesis:

- Mix the synthesized MOF-808 and Zeolite in a ratio of 1:10.
- Put the mixture in a solvent system including DMF and deionized water then stir for approximately 2 hours.
- Ensure that the mixture is added into an autoclave before treating it hydrothermally, 100°C for 12 hours, to create and form the new material.
- Cool the autoclave until it reaches room temperature and then filter it to collect the resulting precipitate to ensure a clear material.
- Wash the resultant material with methanol and deionized water to make sure that any residual solvents are completely removed.
- Dry the hybrid material in a vacuum oven at 80°C for 12 hours.

Characterization of the Hybrid Material:

- X-ray Diffraction (XRD): Perform XRD analysis to determine the crystalline structure of the material and how successful the results were.
- Brunner-Emmett-Teller (BET): BET will examine the surface area precisely through different calculations and data.
- Scanning Electron Microscopy (SEM): Usage of SEM will determine particle size distribution and the precise features of the hybrid material, this will help in understanding the material better.

FIG.2. Scanning Electron Microscopy (SEM) Used for Analysis

- Thermogravimetric Analysis (TGA): Perform TGA to evaluate the thermal stability of the hybrid material under different temperatures.

FIG.3. Thermogravimetric Analysis (TGA)

CO_2 Adsorption Studies:

- High-Pressure Volumetric Analyzer (HPVA): Evaluate the CO_2 adsorption and desorption capture capacity of the material across different pressures and temperatures to find out its performance across multiple cycles. Usage of graphs is recommended to have an accurate view of the performance.

FIG.4. High-Pressure Volumetric Analyzer (HPVA)

System and Prototype

This system offers a sustainable, recyclable, and efficient solution by employing the material (4) within the filter (3) (**Figure 1**), in the ship exhaust. The material starts absorbing CO_2 gas efficiently, The first and second sensors (6) help monitor the CO_2 levels exiting the ships and send accurate reports to governments and relevant authorities to enforce fines if the limits are exceeded. The sensors (6) can also serve another purpose: when the material (4) reaches the saturation stage, the condition where the pores are fully filled, this state is detected using advanced gas sensors (6), one installed before the absorption area and the other after it, allowing for accurate monitoring of CO_2 levels and determining the difference between the gas amount before and after absorption. This precisely determines the effectiveness of the material so that it can be replaced if its effectiveness declines.

When saturation of the material is detected, the material is automatically transported via automated conveyor belts (2) to the regeneration area (1). In the regeneration area (1), the material (4) is discharged from CO_2 using heat up to 80°C and high pressure. It is important to note that the material (4) is unaffected negatively by this heat or pressure, and the CO_2 is collected in designated storage capsules for future use. Afterward, the regenerated material (4) is returned to the storage area (5) for preparation for a new cycle of use in the filter inside the exhaust (3). Additionally, the invention primarily relies on solar energy using solar panels (7).

In the prototype, the following components where used to demonstrate the solution:

ESP 32:

To develop the robotic solution ESP 32 has been used - a microcontroller which has a dual-core Xtensa® 32-bit LX6 CPU that can operate at up to 240 MHz. Along with supporting external flash memory, it has Wi-Fi and Bluetooth (both Classic and BLE) connectivity. It also has 520 KB of internal SRAM. Peripherals such as GPIO, ADC/DAC, PWM, and communication interfaces (UART, SPI, I2C) are all included in the ESP32. For energy efficiency, it supports multiple low-power modes and runs at 3.3V, which makes it perfect for IoT applications and prototyping. Programming environments such as Espressif IDF, Arduino IDE, and PlatformIO can be used to program the ESP32.

NDIR sensor:

A key component in tracking and controlling ship emissions is the NDIR sensor in the CO_2 capturing system. The sensors are installed inside the exhaust system and are used to continuously monitor the amount of CO_2 in the released gasses before and after the capturing materials are placed in the filter, which will be a total of 2 NDIR gas sensors to compare the result and then send data to international bodies. Real-time CO_2 level data is provided by means of sophisticated detecting technologies, including electrochemical and infrared techniques. For environmental rules to be followed, this data is essential. As it alerts companies that CO_2 emissions released exceeded thresholds, causing a possibility of receiving a fine from national and international organizations.

Conveyor Belt:

The conveyor belt in the system was used for transporting the material between the different sections of the system.

Regeneration Area:

In this area, the membranes are heated CO_2 trapped in it to be released and collected in capsules.

Storage:

After regeneration, the material is transported to the storage unit so it can get used again in the exhaust system for capturing CO_2.

This system maximizes the efficiency and longevity of the material, ensuring that it can be reused effectively while continuously capturing and managing CO_2 emissions from the ship's exhaust.

IOT Application:

The software application, coded and designed using Arduino ide application system which plays a pivotal role in managing CO_2 emissions from cargo ships. It interfaces with gas sensors installed in the ship's exhaust system to monitor CO_2 concentrations in real-time.

The software compares data from multiple sensors to ensure accuracy. If CO_2 levels exceed a certain threshold, the application activates a DC motor to initiate the capture process and signals a servo motor to open at 180 degrees for the specific gate to open up for transportation, allowing for the release or storage of captured CO_2.

Brief Explanation of the Drawings of the Prototype design:
Figure 1-A: General top view of the invention
Figure 1-B: General front side view of the invention
Figure 1-C: General backside view of the invention
Figure 2-A: General top view of the invention on the ship
Figure 2-B: General front side view of the invention on the ship
Figure 2-C: General right side view of the invention on the ship

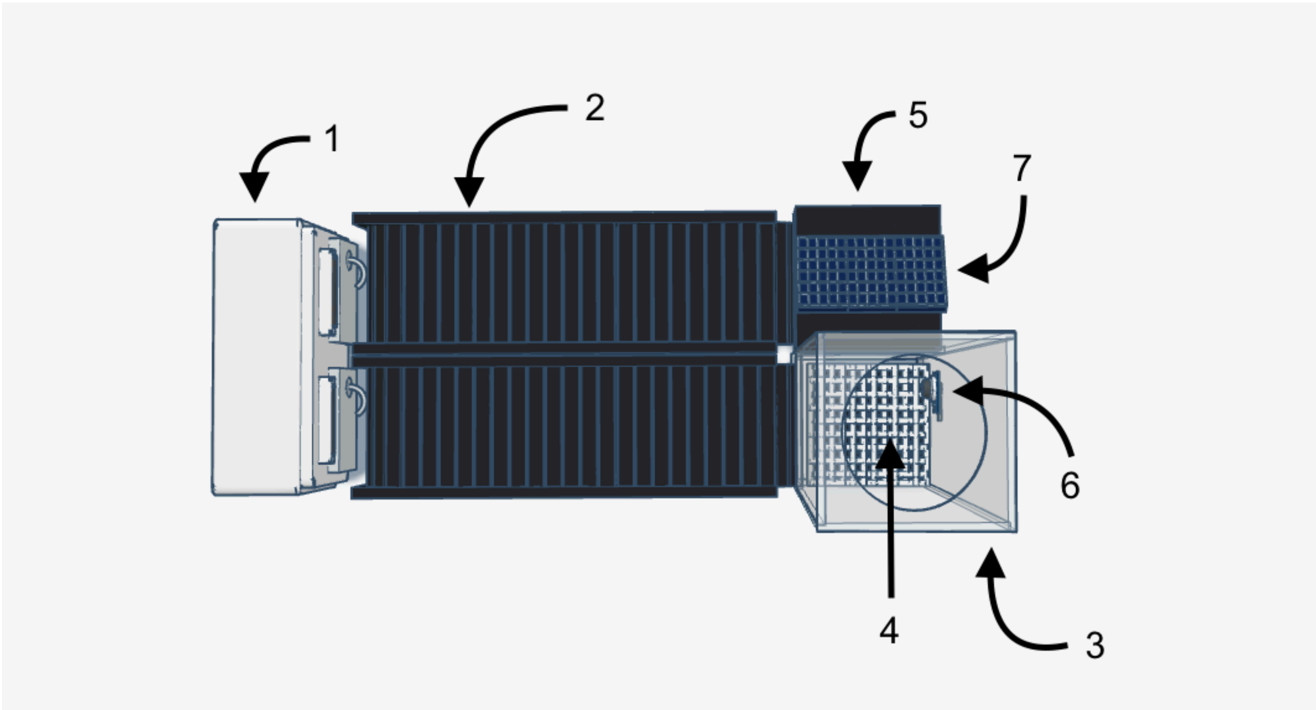


Figure 1-A

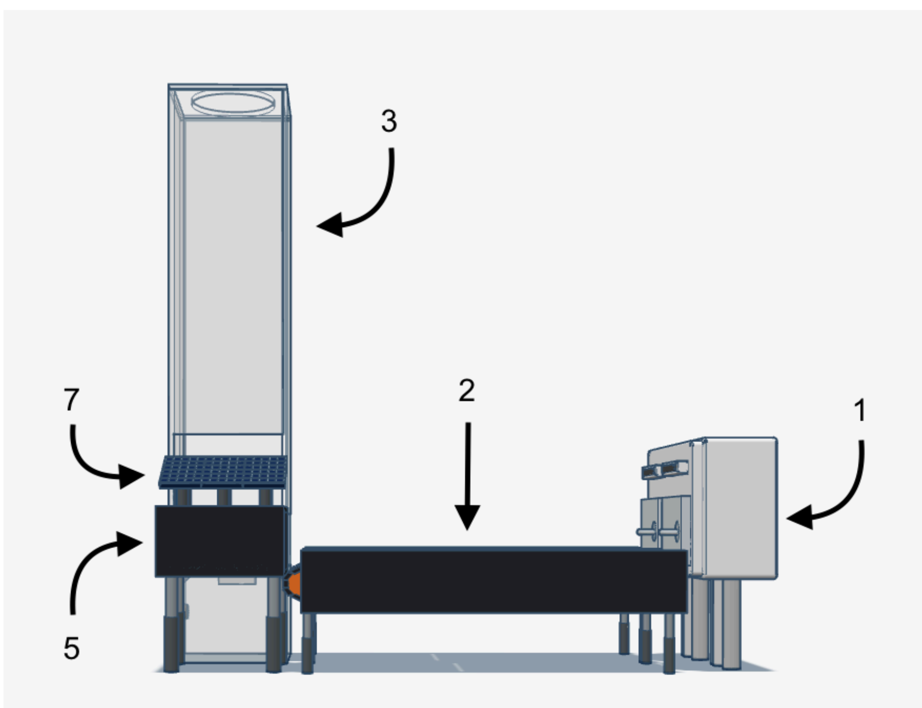


Figure 1-B

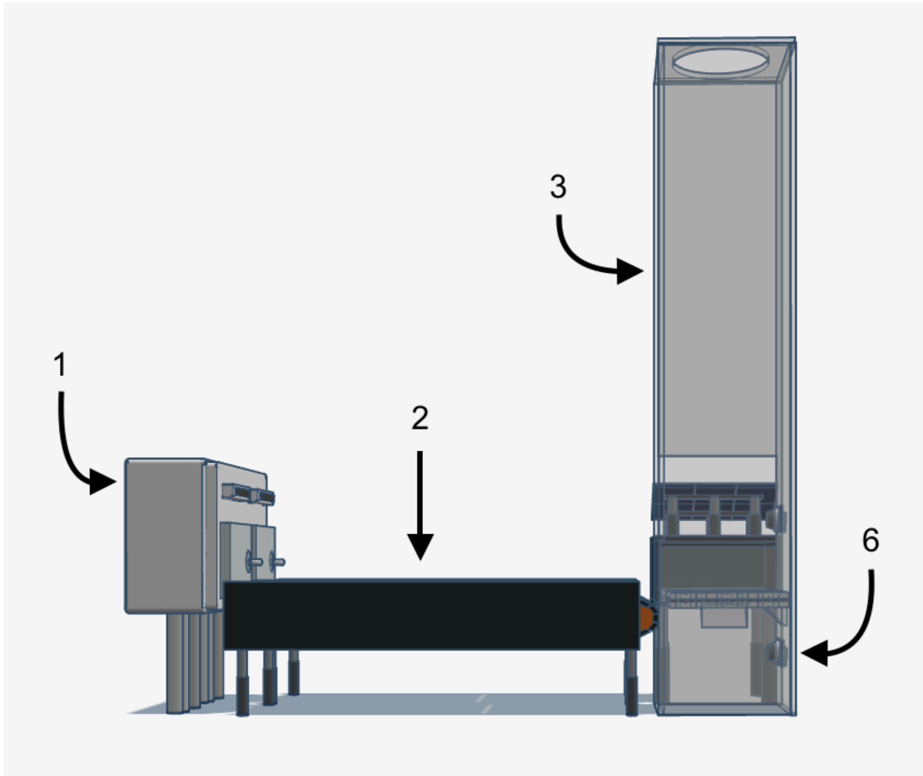


Figure 1-C

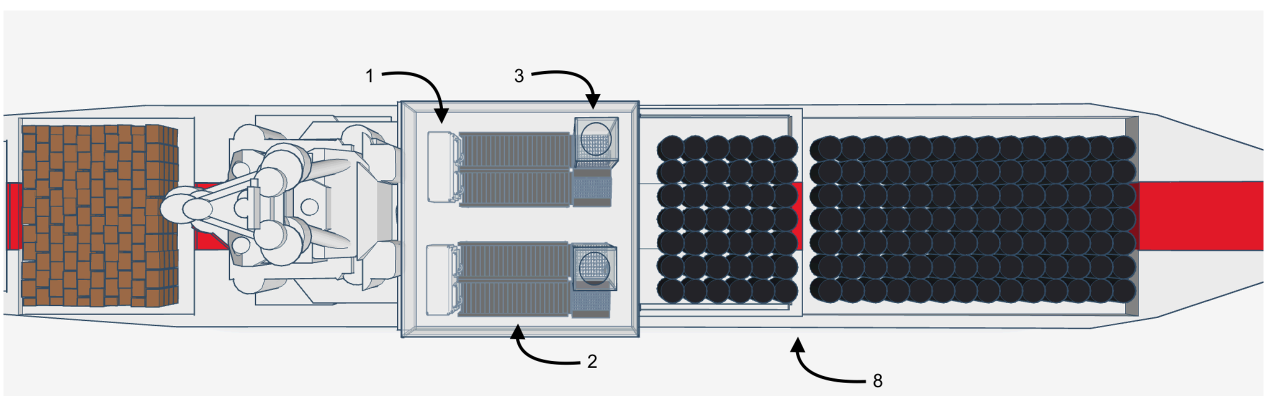


Figure 2-A

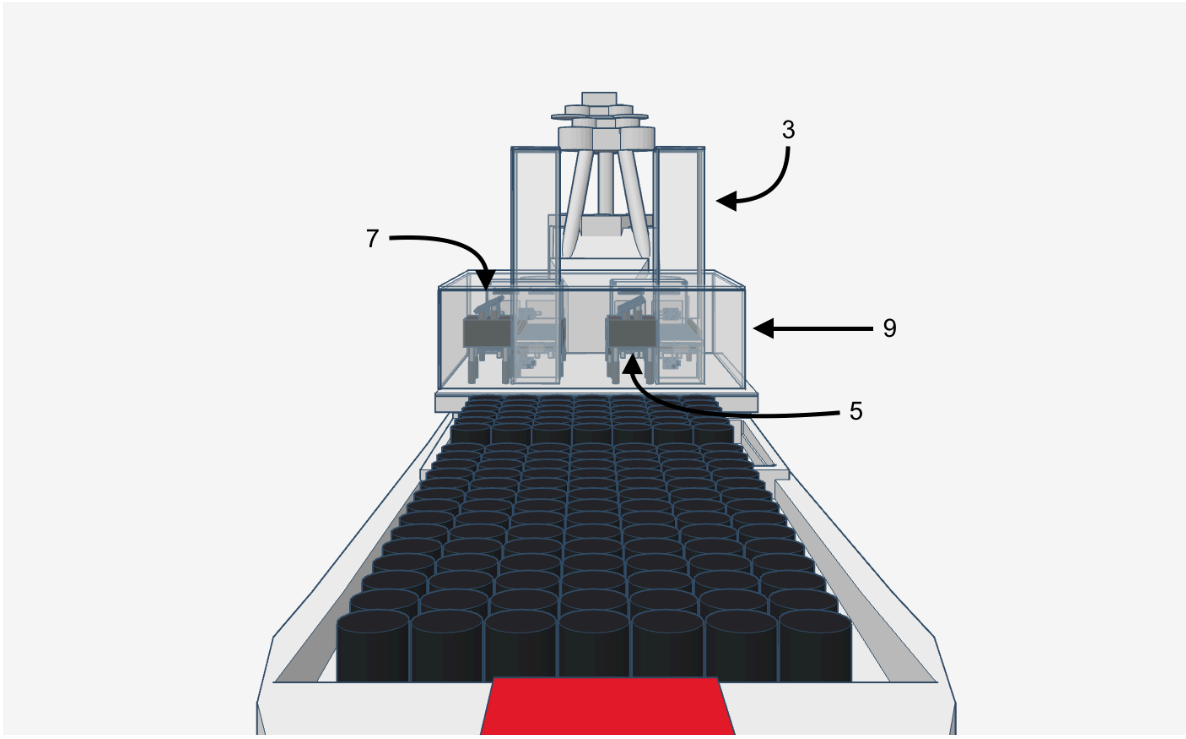


Figure 2-B

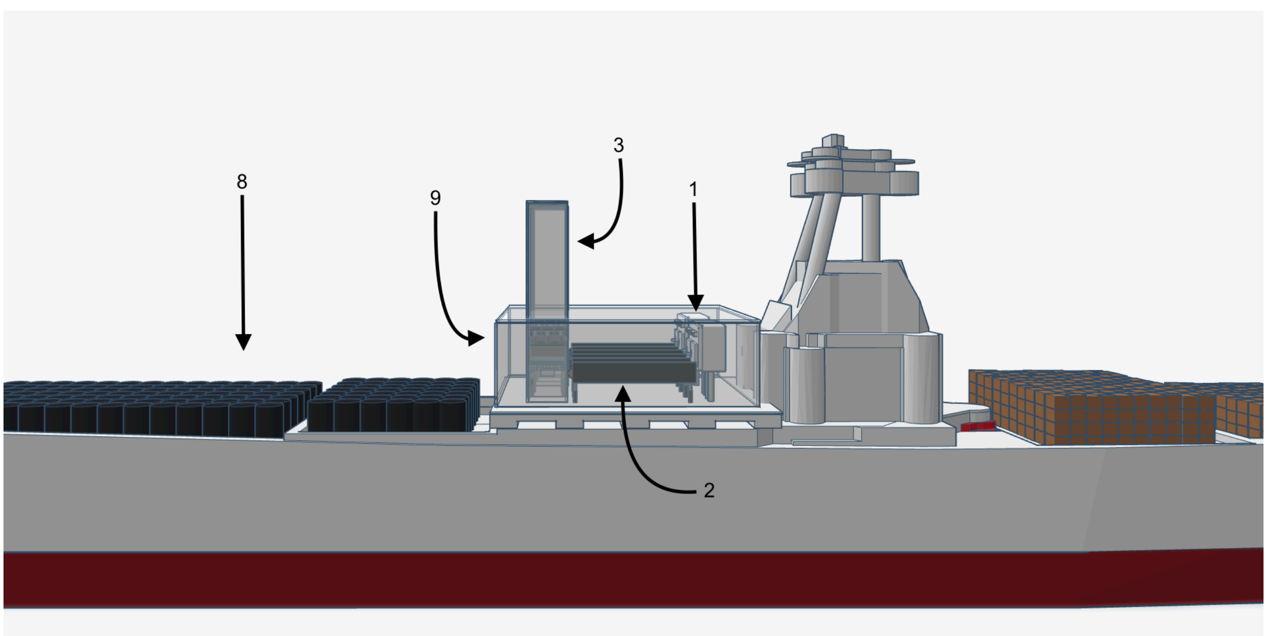


Figure 2-C

PRELIMINARY RESULTS

Zeolite and MOF-808 analysis alone:

Surface area of Zeolite 716.765 m2/g
Weight of Zeolite 0.033 g

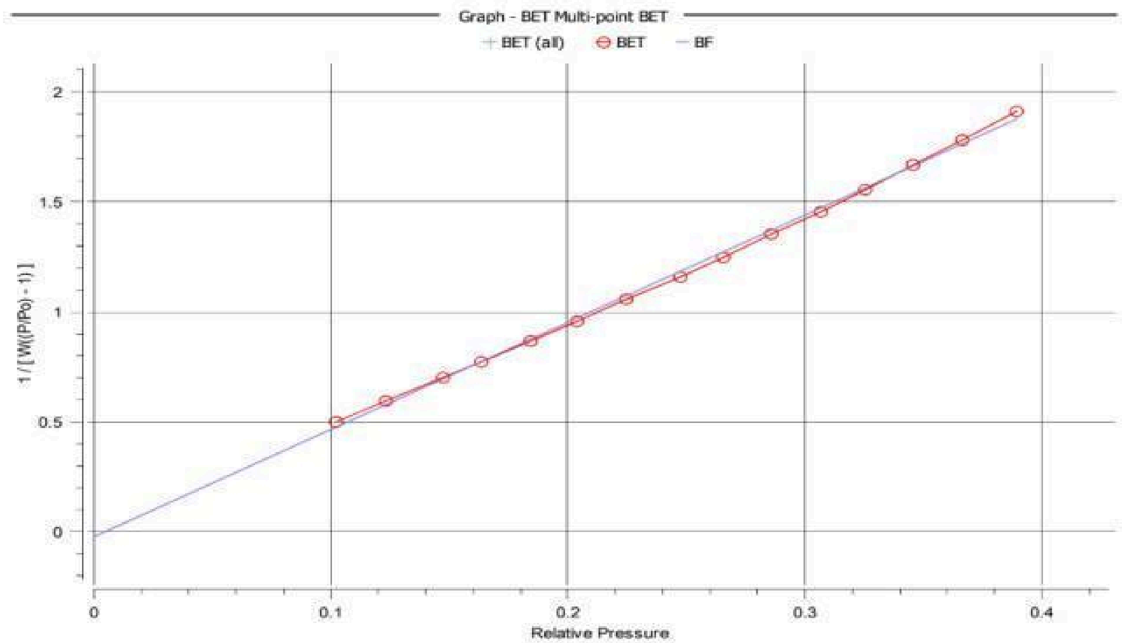


FIG.5. Graph of analysis for surface area of Zeolite by BET

The BET examinations conducted have shown the limited surface area of Zeolite compared to MOF's, however, it is predicted to be enhanced through the composition of the new hybrid material.

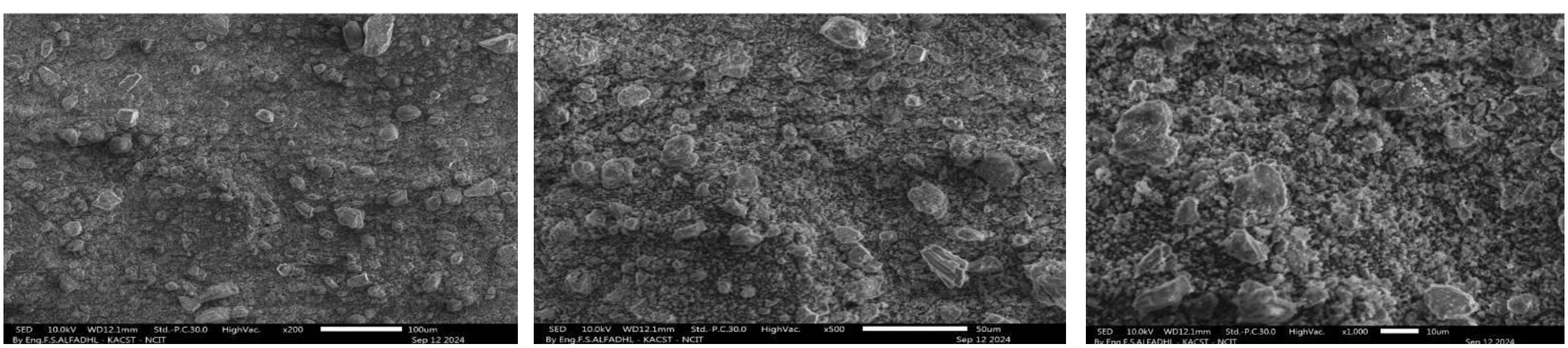


FIG.6. Pictures of Zeolite under SEM

The SEM examinations have shown a good amount and quality of porosity of Zeolite (as shown in FIG.6.) which is a good indicator to its reliability for the hybrid material synthesis.

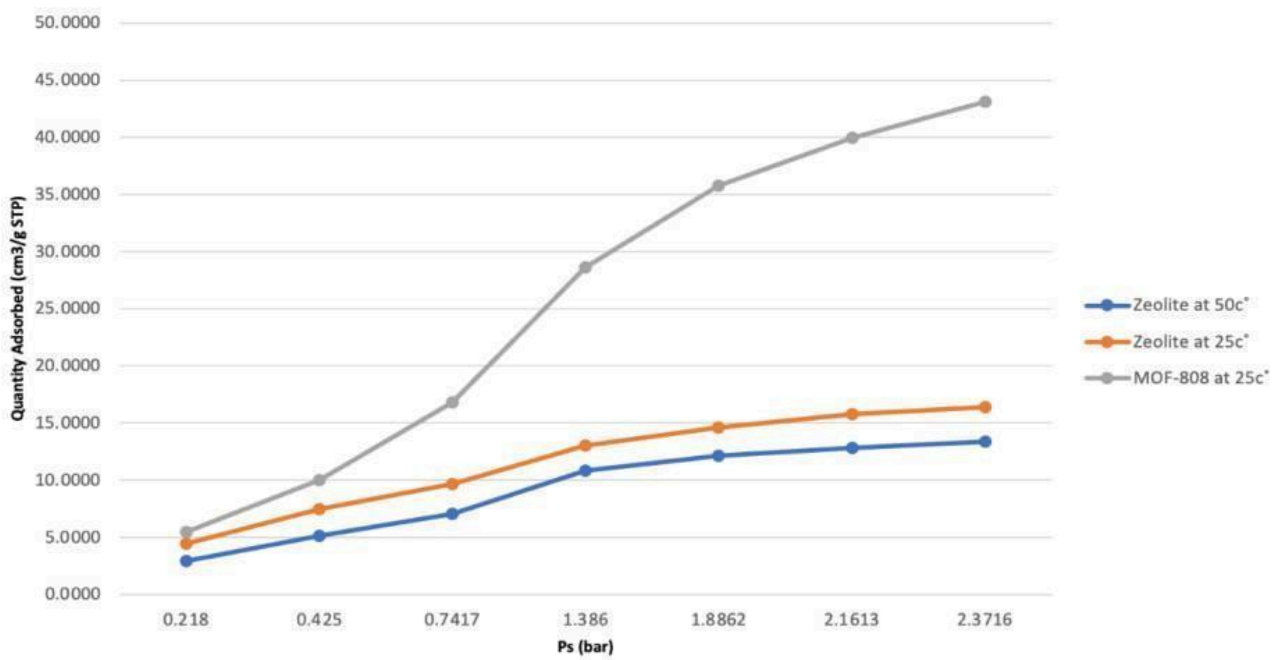


FIG.7. Zeolite and MOF-808 Adsorption Performance by HPVA

The HPVA examinations conducted have shown limited adsorption capabilities for Zeolite in different pressures as expected, however, MOF-808 has shown an excellent performance in all pressure conditions (as shown in FIG.7.), yet, it is predicted to increase even more in the hybrid material.

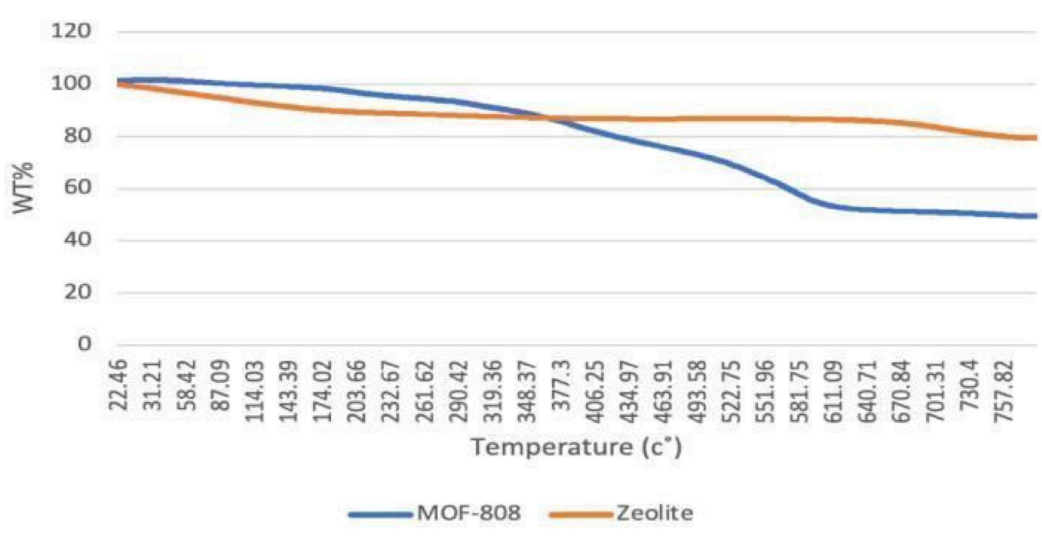


FIG.8. Zeolite and MOF-808 Thermal Stability by TGA

The TGA examinations have shown an excellent thermal stability of Zeolite with low weight loss throughout very extreme temperature conditions, however, Mof-808 lost a lot of its weight percentage meaning that it degraded (as shown in FIG.8.) .

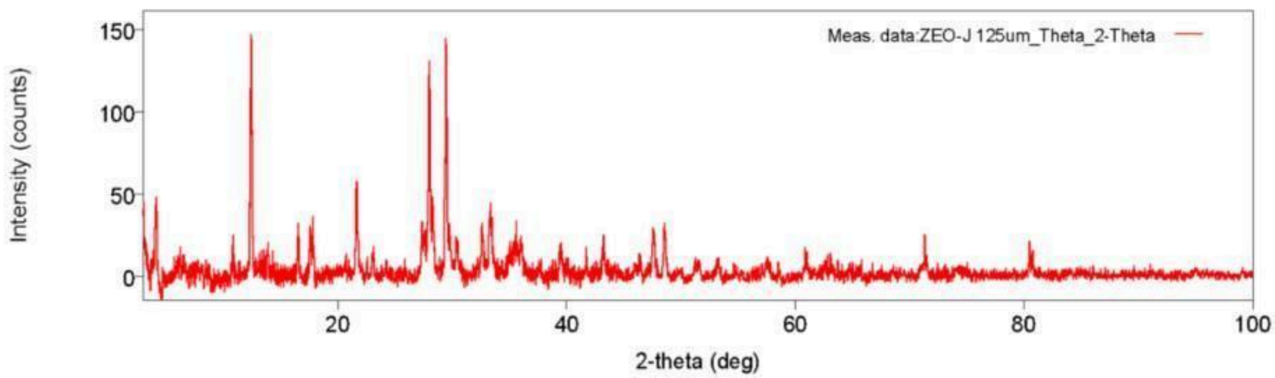


FIG.9. Zeolite Crystalline Structure by XRD

The XRD examinations conducted have shown different peaks of density at different degrees (as shown in FIG.9.) . This can help identify the structure chemically which may be needed in the future of the research.

FUTURE WORK

- The research will continue to examine the new synthesized hybrid material, and it will follow all the inspections like of Zeolite and MOF-808.
- The ratio used of the two materials will also be further studied and tuned to acquire low costs but still accomplish high capture rates.
- Most probably, a good ratio will be met by adding more Zeolite than MOF-808 in the material to reduce the cost of synthesis while keeping a high surface area.
- The material will be applied in power plants and, potentially, different transportation vehicles in their exhaust system to capture the CO_2 emissions before its release in the atmosphere, therefore, it will be tuned to perform effectively.

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