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Recent Scenario and Integrated Sustainable Method for CCUS in India

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Abstract

Abstract The Earth's average surface temperature has risen by roughly 1.55°C since the pre-industrial era of 1850–1900, according to the World Meteorological Organization (WMO, 2024). Presently, the planet is facing a rapid phase of global warming primarily driven by human-induced carbon dioxide (CO_2) emissions, a major contributor to climate change and extreme weather phenomena. This research focuses on creating a cost-effective, small-scale prototype to capture CO_2 from stationary sources such as coal-fired power plants, cement manufacturing plants, and steel industries. The captured carbon is then converted into calcium carbonate ($CaCO_3$), a versatile compound with practical applications in construction, cement production, and as a filler in paper and plastic industries. The method relies on solvent-based absorption—an established post-combustion carbon capture method within the broader Carbon Capture, Utilization, and Storage (CCUS) paradigm. In addition to capture, the study explores long-term underground geological storage options such as saline aquifers and depleted gas fields, as well as utilization pathways that transform CO_2 into valuable industrial products. This integrated approach not only prevents CO_2 emissions from reaching the atmosphere but also promotes sustainable reuse and permanent containment. The proposed strategy has the potential to contribute significantly to climate mitigation efforts and help India advance toward its Net Zero Greenhouse Gas (GHG) emissions target by 2050.

1. Introduction

Carbon Capture, Storage, and Utilization (CCUS) technology which captures carbon and stores it from being released by industries and energy-related fossil burning sources into the air. India is the world's second most populous nation with a rapidly growing economy. Due to the fast increase in global economies and population, which requires a greater energy supply on a worldwide scale, fossil fuels will continue to play an important role. India is the 3rd largest emitter of CO_2 in the world after China and the US (Atanu Mukherjee & Saurav Chatterjee 2022). UK Research and Innovation (UKRI) and Department of Science and Technology (DST) in India are aiming to identify emerging research priorities in the area of CCUS. This paper focuses on a more technological method known as the Carbon Capture, Utilization and Storage The impact of climate change is soaring continuously due to the environmental burden accumulated for the past two decades. This technique will evaluate the technological, and environmental aspects of each type of CCUS technology. LCA evaluates the environmental performance of each technology to help in decision-making and reduce the environmental impact. The application of LCA will be useful for product development and improvement, strategic planning and marketing Since the start of the industrial revolution, global greenhouse gas emissions have been increasing, and the greenhouse effect has become more and more serious. Climate change has become a serious challenge to be faced. According to statistics, CO_2 is the main gas causing the greenhouse effect, accounting for more than 70% of the global greenhouse gas, and the rest are methane, nitrous oxide, and various fluorinated gases. Carbon capture technologies rely mainly on two basic principles, chemical absorption and physical separation. Both constitute the basis of technologies that are well-known in the oil and gas industry for natural gas processing such as amine solvents and solid adsorbents. The technologies focusing on CO_2 removal before combustion are classified as Pre combustion capture technologies, the most advanced ones, present in the Oil and Gas industry. Post-combustion captures technologies, on the other hand, focus on CO_2 removal from flue gas, where the concentration of CO_2 is lower, a challenge that recent technology developments have been focusing on to overcome in an increasingly efficient manner. Lastly, oxyfuel combustion focuses on modifying the combustion process so that the flue gas has a high concentration of CO_2 to enable an easier separation (Alphen et al.2009)

India is the 3rd largest emitter of CO_2 in the world after China and the US (Atanu Mukherjee & Saurav Chatterjee 2022), with estimated annual emissions of about 2.6 gigatonne per annum (gtpa). The Government of India has committed to reducing CO_2 emissions by 50% by 2050 and reaching net zero by 2070 (Atanu Mukherjee & Saurav Chatterjee 2022). The growth of renewable power capacity has been one of the key success stories of the clean energy transition in India; however, the power sector only contributes to about 1/3 rd of the aggregate CO_2 emissions, which will continue to abate as renewables increasingly replace fossil fuel-based power generation.

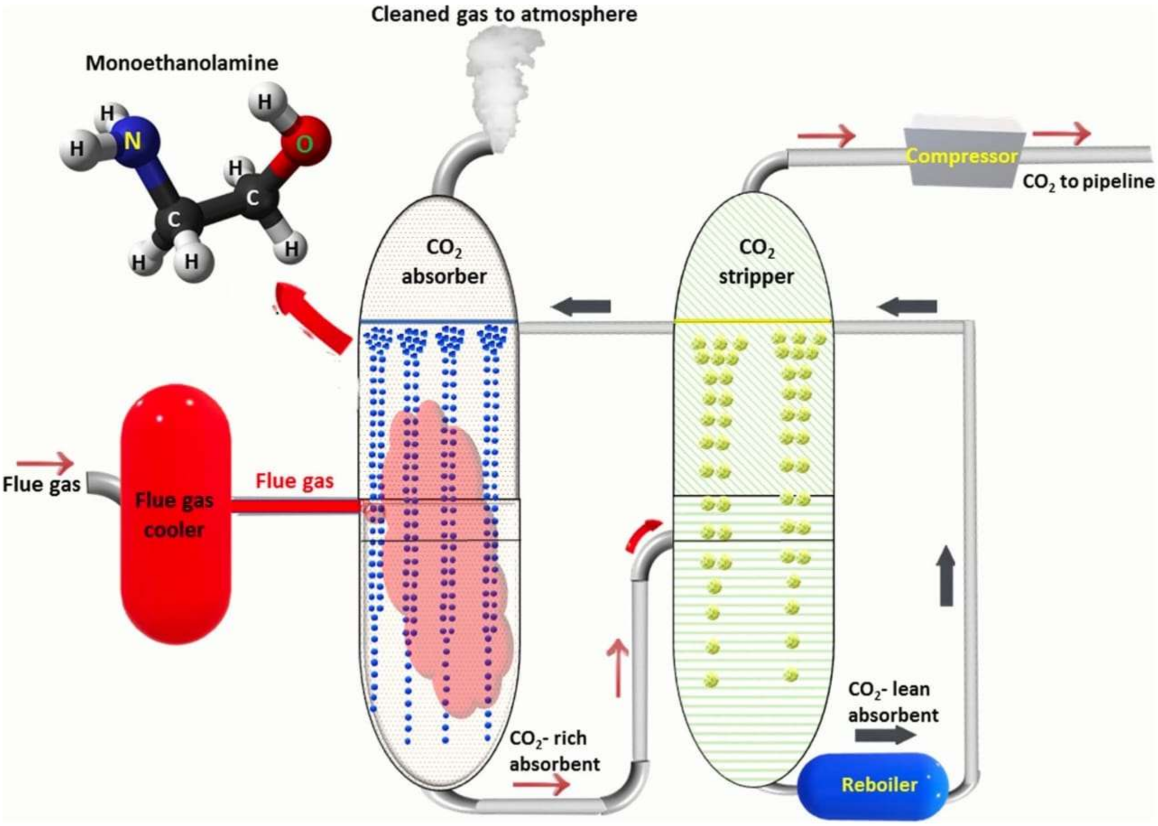


Fig.1 A simple Process of Capturing Carbon Dioxide (Osman et al., 2020).

World Metrological Organization (WMO) reported that 2023 was the warmest year on record globally, with the global average near-surface temperature at 1.45 ± 0.12 °C above the pre-industrial baseline (1850-1900) (WMO 2023)" Let's see the variation of concentration of carbon dioxide with the help of a graph of last some years provided by WMO.
The report suggests that carbon dioxide (CO_2), a major greenhouse gas, is a significant driver of this warming. By examining the variation in CO_2 concentration over the last several years (using data from the WMO), we can better understand how this greenhouse gas has contributed to the warming trend. A graph of the CO_2 concentration data would visually show how CO_2 levels have been changing in recent years.

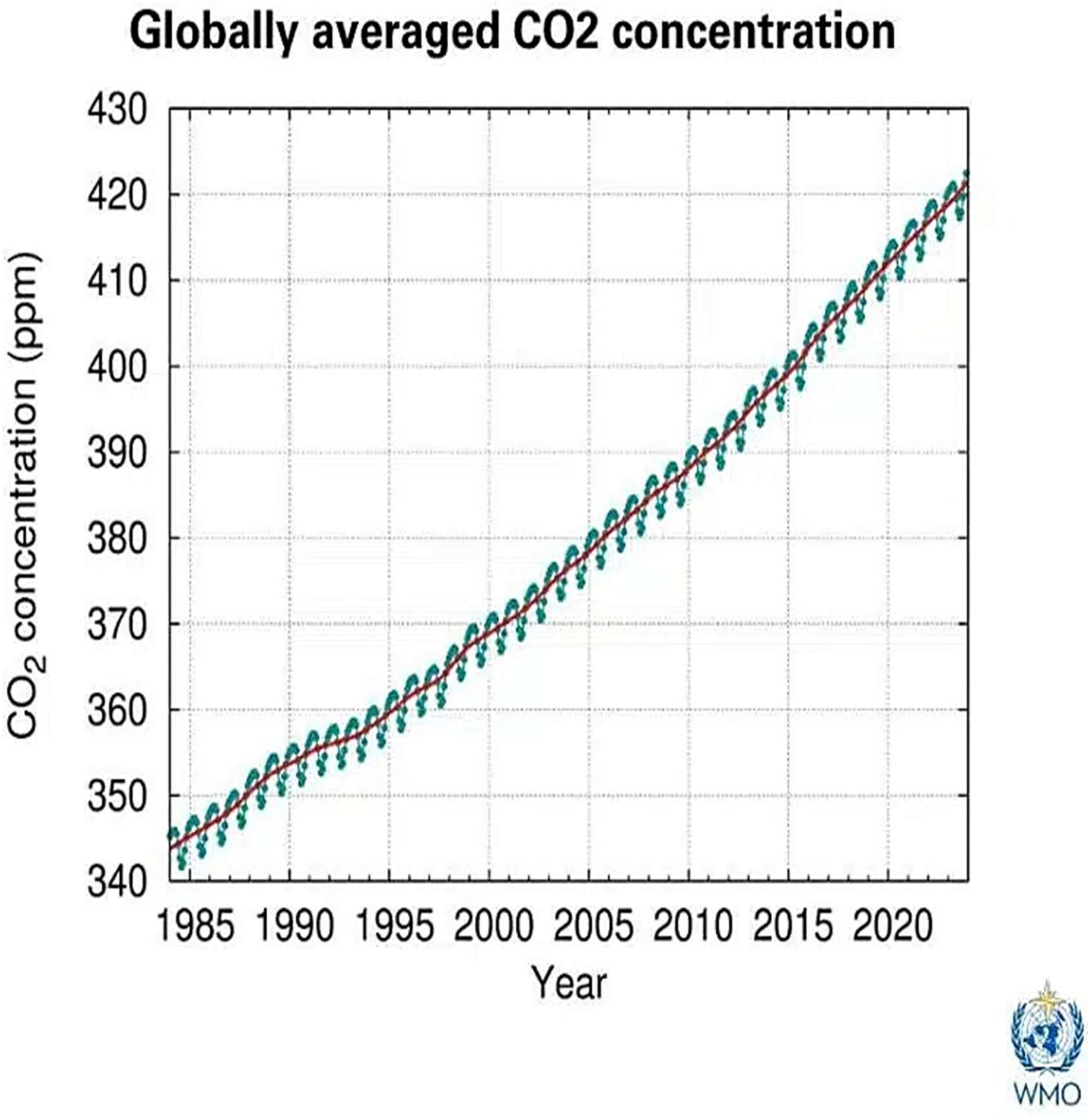


Fig.2 Veriation Of Concentration Of CO_2 (WMO Report 2023).

1.1 Problem Statements

The world is facing increasingly extreme weather and climate events, including rising temperatures and fewer cold days. One of the major drivers of climate change is the emission of greenhouse gases (GHGs), particularly from the burning of fossil fuels for energy. Among these, carbon dioxide (CO_2) is a key contributor.

1.2 Objective of Study

This project is focused on exploring practical and affordable solutions for capturing and using carbon dioxide (CO_2) on a small scale. With growing concerns about climate change and the need to reduce greenhouse gas emissions, the project aims to design a low-cost experimental setup that can effectively capture CO_2 from the atmosphere or other sources. It will investigate simple and efficient capture methods that are suitable for small-scale use, making them accessible for educational, research, or local applications. In addition, the project will demonstrate how the captured CO_2 can be put to good use in various practical ways, instead of letting it go to waste. Finally, it will assess the environmental impact of these techniques and how they can contribute to reducing overall carbon emissions. The main objectives of the project are:

1. To develop a low-cost, small-scale experimental setup for capturing carbon dioxide.
2. To investigate efficient and affordable carbon capture techniques suitable for small-scale applications.
3. To demonstrate practical methods for utilizing captured CO_2 in various applications.
4. To assess the environmental benefits of CO_2 capture and utilization in reducing carbon emissions.

2. Theoretical background

To achieve the Paris Agreement target of keeping the global temperature rise well below 2°C—and ideally limiting it to 1.5°C above pre-industrial levels—a significant and fundamental transformation of the industrial sector will be necessary. The UK and India, as signatories to the Paris Agreement, have committed to reaching net-zero emissions—by 2050 for the UK and by 2070 for India. Both nations understand that Carbon Capture, Utilization and Storage (CCUS) will play a key role in achieving these targets.

2.1 Current scenario in India

India is the 3rd largest emitter of CO_2 in the world after China and the US. The Government of India has committed to reducing CO_2 emissions by 50% by 2050 and reaching net zero by 2070. CCUS technology in India is at initial stage. Currently only 8 R and D institutions leading the CCUS research in India i.e, IIT Bombay, National Chemical Laboratory, IIT Delhi, National Environmental Engineering Research Institute. CCUS technology provides a good solution against the global climate change (Sun et al.2017). India's CO_2 emissions in 2023 were 2.8 Gt (2.8 billion metric tons) (IEA Report 2023).

2.2 Capture Technologies

Carbon capture technologies work mainly in two ways: using chemicals to absorb CO2 or using physical methods to separate it. These methods are already used in the oil and gas industry, especially in natural gas processing, with tools like amine solvents and solid materials that trap gases (Li et al.2018). There are three main types of carbon capture: -

1. **Pre-combustion capture** – This removes CO2 before burning the fuel. It's the most advanced method and is already used in the oil and gas industry.
2. **Post-combustion capture** – This takes CO2 out of the gases released after burning fuel. Since CO2 levels are lower in these gases, it's more challenging, but new technologies are making it more effective.
3. **Oxyfuel combustion** – This changes the way fuel is burned so that the gases released have more CO2, making it easier to separate and capture.

method is aimed at reducing CO2 emissions in different ways. Depending on when and how the gas is captured. These are the main types-Each

- **Solvents:** This is the most common method used today. CO2 is absorbed into a liquid, either through a chemical reaction or by physical means. The most popular solvents are based on amines, which are widely used in industry.
- **Solid Adsorbents:** CO_2 gas moves through a container filled with solid materials that can capture it. These materials work best at high pressure. Once they are full, they are cleaned and reused by either heating them (called Temperature Swing Adsorption or TSA) or by lowering the pressure (called Pressure Swing Adsorption or PSA).
- **Membranes:** CO_2 is separated from other gases using a thin barrier called a membrane. This membrane lets CO_2 pass through more easily than other gases, helped by pressure differences on each side.

2.3 Utilization Technologies

Once CO_2 is captured, it can either be stored or used. It can be used directly in different industries, or it can be used as a raw material to make other chemicals and products. Direct and indirect use of captured CO_2 are-

- **Enhanced Oil Recovery (EOR):** CO_2 is injected into underground oil and gas fields to help extract more oil. This is the most common way captured CO_2 is used today. (IEA, 2019b)

- **Other Uses:** High-purity CO_2 is used in various industries. It's used in food production (like carbonating drinks), in medical applications, and as a cooling fluid in factories. It also works as a cleaning solvent (such as in dry cleaning or for removing caffeine from coffee). CO_2 can also help plants grow faster in greenhouses and algae farms.

- **Chemicals and Polymers:** The main use of CO_2 in chemicals is to make urea, which is produced during ammonia manufacturing. CO_2 can also be turned into building blocks (monomers) for making plastics like polycarbonates. Another method involves using microbes to convert CO_2 into useful chemicals. (IEA, 2019b)

- **Fuels Production:** CO_2 can be combined with hydrogen to produce methanol, which can then be made into different fuels. In another process, CO_2 is first converted into carbon monoxide (using the reverse water-gas shift reaction) and then combined with hydrogen through Fischer–Tropsch synthesis to create gasoline, diesel, and other fuels. (Styring and Dowson, 2021).

2.4 Storage & Transport Technologies

CO_2 can be stored by injecting it deep underground into places like saline aquifers or old oil and gas reservoirs. In these spaces, the CO_2 is trapped under layers of rock because it is lighter than the surrounding fluids—this is called structural trapping. Over time, some of the CO_2 can also slowly react with the rocks and turn into solid minerals, helping to keep it safely stored for the long term.
Captured CO_2 can be transported using pipelines, trucks, road way or ships. Pipelines are the most widely used and cost-effective method for large-scale CO_2 transport, particularly over short to medium distances. Before transport, CO_2 is typically compressed into a supercritical state, which improves efficiency and reduces volume. The choice of transportation method depends on the distance, volume, and specific infrastructure available. Large-scale CO_2 transportation generally uses pipelines (Zhang et al.213).

3. Experimental Setup and Methodology

At Saharsa Engineering College, Saharsa, we developed a model for capturing carbon dioxide from stationary sources such as coal power plants, cement factories, and steel plants. The equipment and setup required for developing this model are described below.

3.1 Equipment's Required

- Source of CO_2 (ex-coal)
- Mono ethanolamine (C_2H_7NO)
- A small exhauster pump.
- Ca $(OH)_2$ (Lime Water)
- Three Containers (Reactor, Adverse Reactor and Limewater Container).
- Induction Stove

Coal:
Coal is a combustible black or brownish-black sedimentary rock composed mostly of carbon, along with hydrogen, sulfur, oxygen, and nitrogen. It forms from the remains of ancient vegetation that accumulated in swamps and peat bogs millions of years ago.

Fig.3 Coal

Table 1: Different types of coal and percentages of carbon contents.

Type	Carbon Content	Moisture	Heat Content	Use
Peat	~55%	High	Low	Fuel in some regions
Lignite	25–35%	Very high	Low	Electricity generation
Sub-bituminous	35–45%	Moderate	Medium	Electricity generation
Bituminous	45–86%	Low	High	Power and steel industries
Anthracite	86–97%	Very low	Very high	Heating and metallurgy

Mono ethanolamine (C_2H_7NO): Mono ethanolamine (MEA) is an organic compound with the chemical formula C_2H_7NO or $HO–CH_2CH_2–NH_2$. It is also called:

- Ethanolamine
- 2-Aminoethanol

It has both an amine group ($-NH_2$) and a hydroxyl group (-OH), making it both an alcohol and a primary amine.

Fig.4 C_2H_7NO

MEA in Carbon Capture:

- MEA is one of the most commonly used solvents in carbon capture and storage (CCS) systems: CO_2 reacts with MEA to form carbamate, which is later heated to release pure CO_2 for sequestration.
- MEA-based systems are used in post-combustion CO_2 capture from power plants.

However, MEA has drawbacks:

- Corrosive nature
- Degradation at high temperatures
- Energy-intensive regeneration
- Newer amines and blends are being developed to overcome these issues.

A small exhauster pump:

This is the motor which is used for mixing the fuel gas with mono ethanolamine in reactor. The motor sucks the fuel gas from one end from the chimney and throw from other end with pressure so that fuel gas easily mixes with the solvent that is mono ethanol amine.

Fig.5 small exhauster pump

Cyclonic Separator:

This is the cyclonic separator. The main function of cyclonic separator is to remove dust coming with fuel gas. It is used just before the reactor.

Fig. 6 Cyclonic Separator

Reactor:

This is the reactor which contains mono ethanol amine (C_2H_7NO). In this container carbon dioxide present in fuel gas only react with mono ethanol amine and make carbon dioxide reach solvent.

Fig.7 Reactor

Adverse Reactor:

This is adverse reactor, the carbon dioxide rich solvent allows to move in adverse reactor, where by heating it at 120ºC to 130ºC an adverse reaction is happened in which carbon dioxide separated from carbon dioxide rich solvent.

Fig.8 Adverse Reactor

Lime Water Container:

This is the lime water container which contains lime water Ca $(OH)_2$. The carbon dioxide separated in adverse reactor is allow to move in lime water container, where it reacts with lime water and make water and very useful product calcium carbonate (CaCO3) which make the water milky in color.

Induction Stove

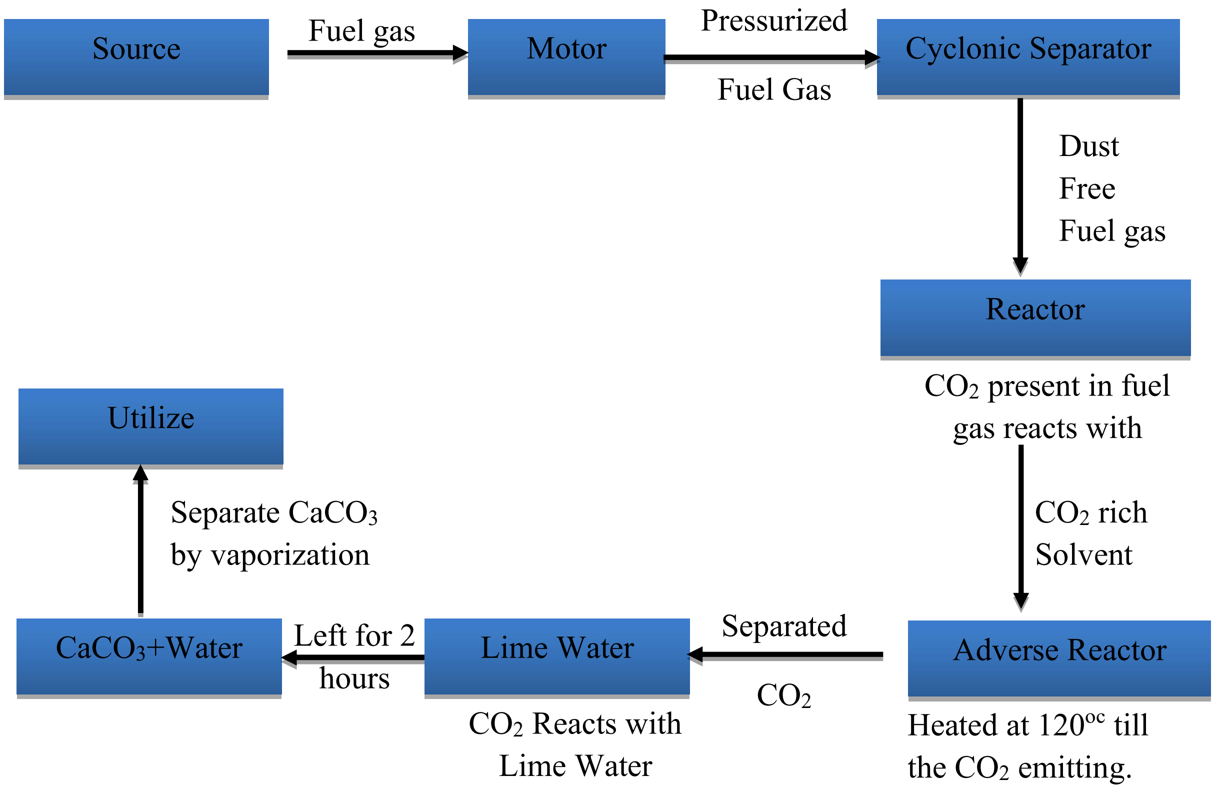
This is the Induction stove which is used to heat the adverse reactor so that adverse reaction will happen.

Fig.9 Lime water container

Fig.10 Induction stove

3.2 Methodology

Flow Chart for the adopted methodology



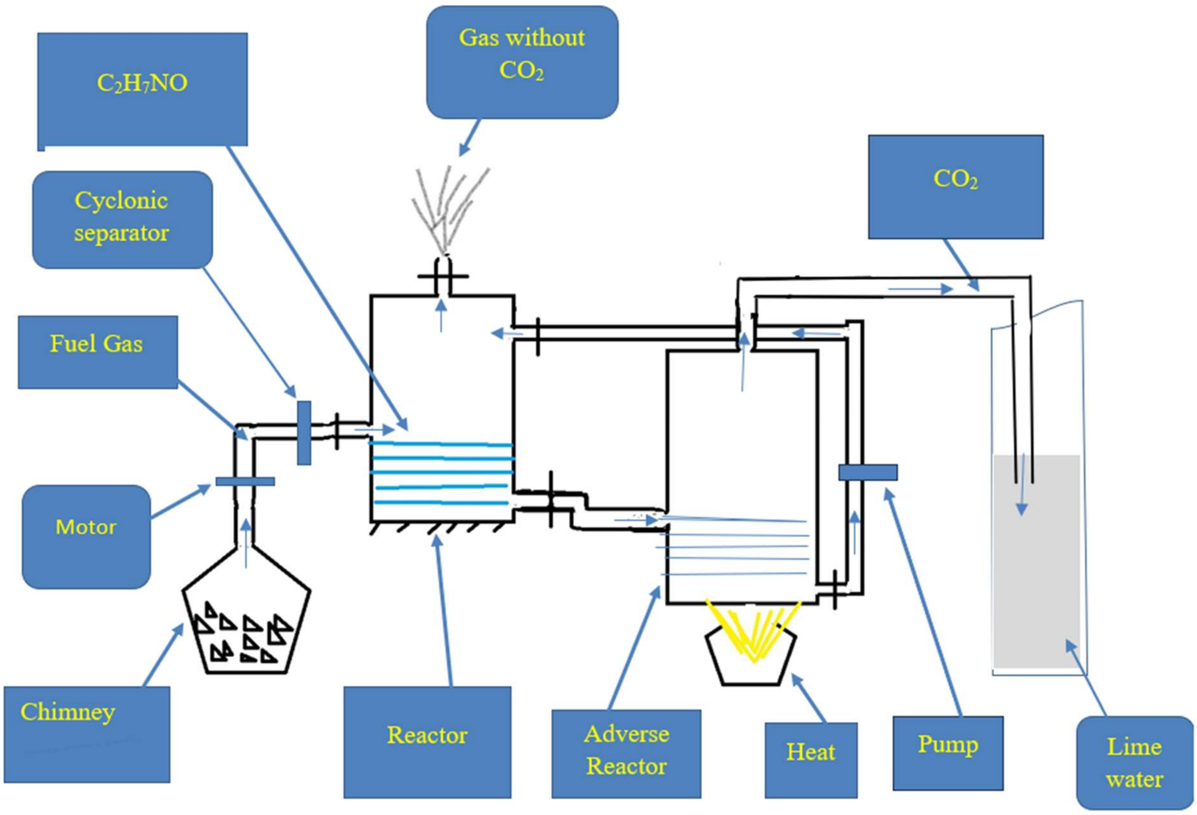


Fig.10 Flow Chart of Proposed Methodology

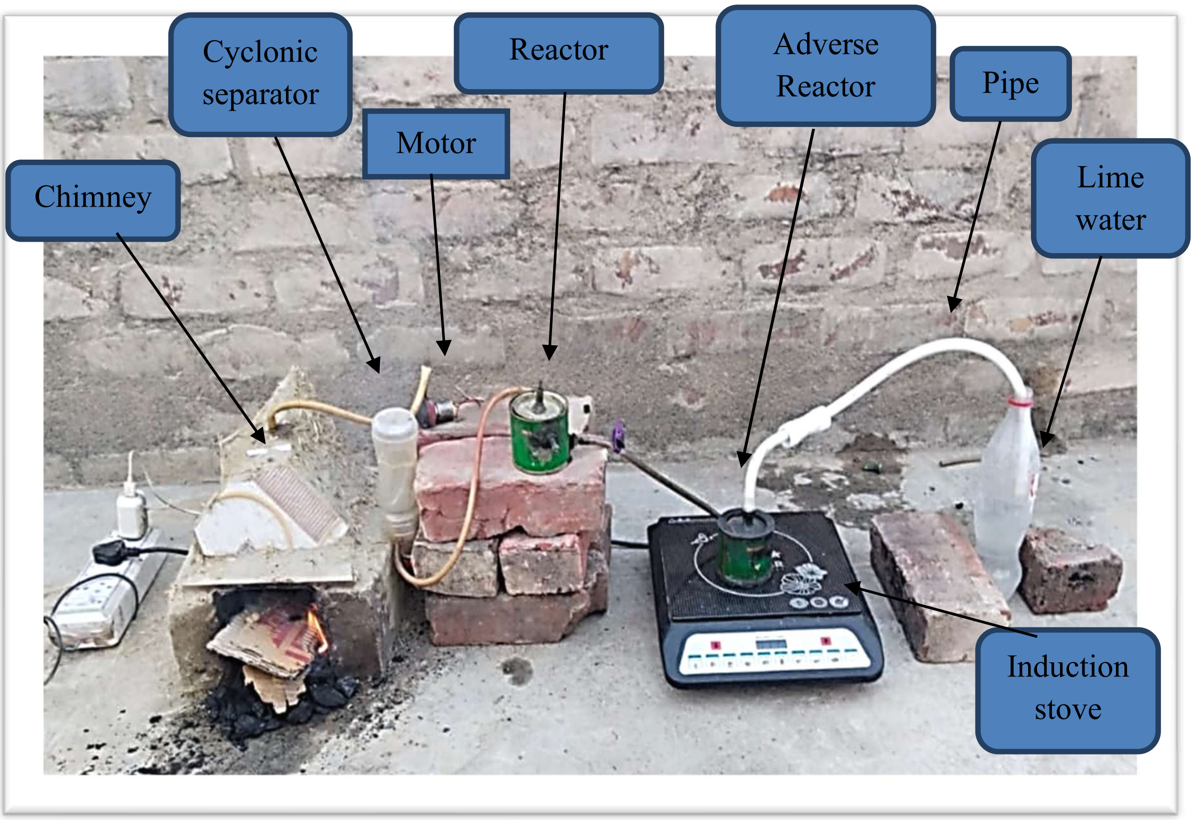


Fig.12 Final Experiment Setup for CCUS at Saharsa College of Engineering Saharsa

3.3 Different Steps should be Flowed for Experimental setup

1. Set up the equipment as shown in flow chart.
2. Pour mono-ethanolamine (C_2H_7NO) in reactor.
3. Transfer the fuel gas to reactor from source.
4. In reactor mono-ethanolamine react with CO_2 and other gases remove in atmosphere.
5. Reacted CO_2 rich solvent transfer in adverse-reactor.
6. Further heat the adverse-reactor at 110^{oc} to 130^{oc} so that reaction will reverse i.e., CO_2 will separate from the solvent.
7. Separated CO_2 is further allowed to flow in lime water content container.
8. Carbon dioxide reacts with lime water and forms calcium carbonate (s) and water (l), due to calcium carbonate become milky as shown in figure 4.11
9. Left the` carbon dioxide (CO_2) reacted lime water for an hour.
10. Whipt ppt of calcium carbonate ($caco_3$) is settled down figure 4.11
11. Separate the calcium carbonate and further use for different purposes such as building material, in medical field, used in manufacturing of paints, paper and plastic …etc.

3.4 Lime Water Test of Carbon Dioxide (CO_2)

Processes:

a. Allow the separated gas to mix with lime water properly.
b. If the colour of lime water changes from colour less to milky colour, then it is verified that separated gas is nothing but carbon dioxide. The chemical reaction is shown below.

$$\mathbf{Ca\ (OH)2\ (aq) + CO2(g) \rightarrow CaCO3(s) + H_2O(I)}$$

Calciyumhydroxide (Lime water) — Carbon dioxide — Calciumcarbonate (White ppt) (Makes limewater milky) — Water

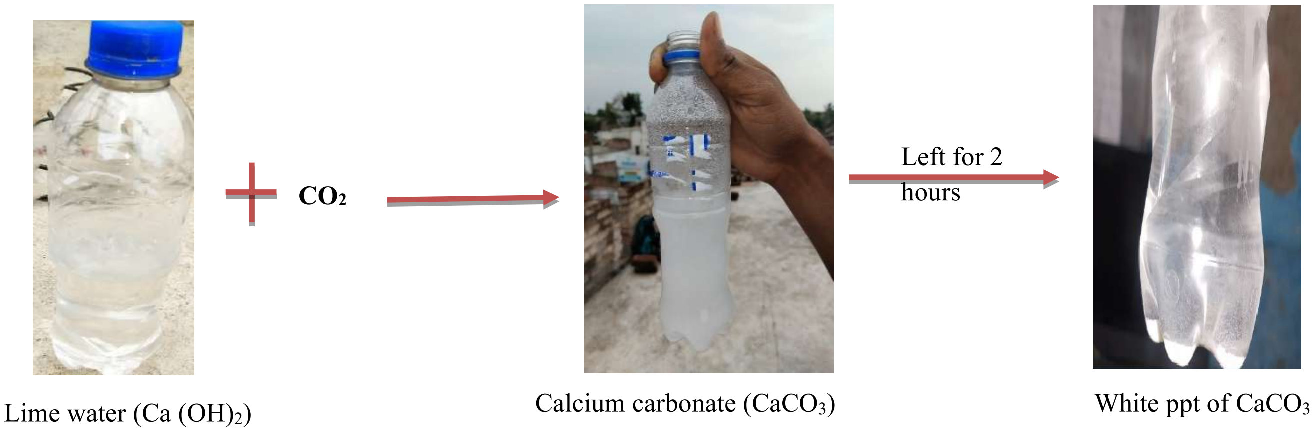


Fig.13 Reaction of lime water with CO_2

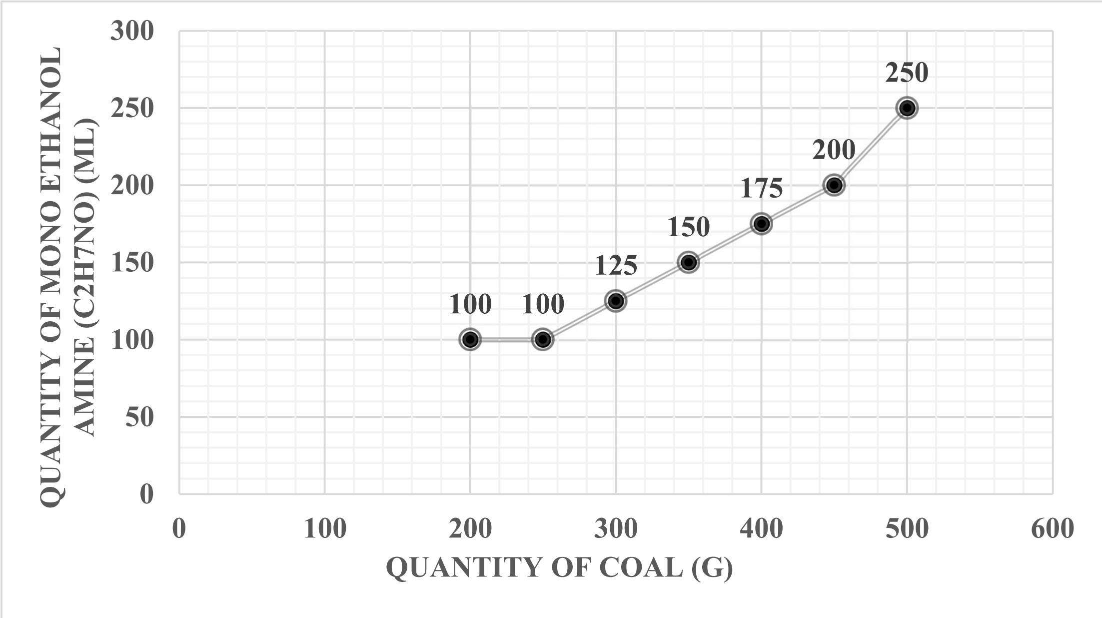
4. Data Collection and Analysis

Now we are sharing the data which are calculated during the experiment work regarding Capturing and Utilizing the carbon dioxide present in fuel gas. The implementation of CCUS technology involves a comprehensive approach to data collection, calculation, and analysis to ensure efficiency, safety, and sustainability.

Table 2: Collection of Data During Experiment

Experiment no.	Quantity of coal(g)	Quantity of mono ethanol amine (C_2H_7NO) (ml)	Quantity Of lime water ($Ca(OH)_2$) (ml)	Generated calcium carbonate ($CaCO_3$) (g)
01	**200**	**100**	**200**	**47.5**
02	**250**	**100**	**250**	**70**
03	**300**	**125**	**250**	**90**
04	**350**	**150**	**300**	**105**
05	**400**	**175**	**325**	**120**
06	**450**	**200**	**400**	**140**
07	**500**	**250**	**450**	**157.5**

This table shows the variation of requirements of quantity of mono ethanolamine for the certain amount of coal used in industries.



Fig,14 Variation of C2H7NO with Coal.

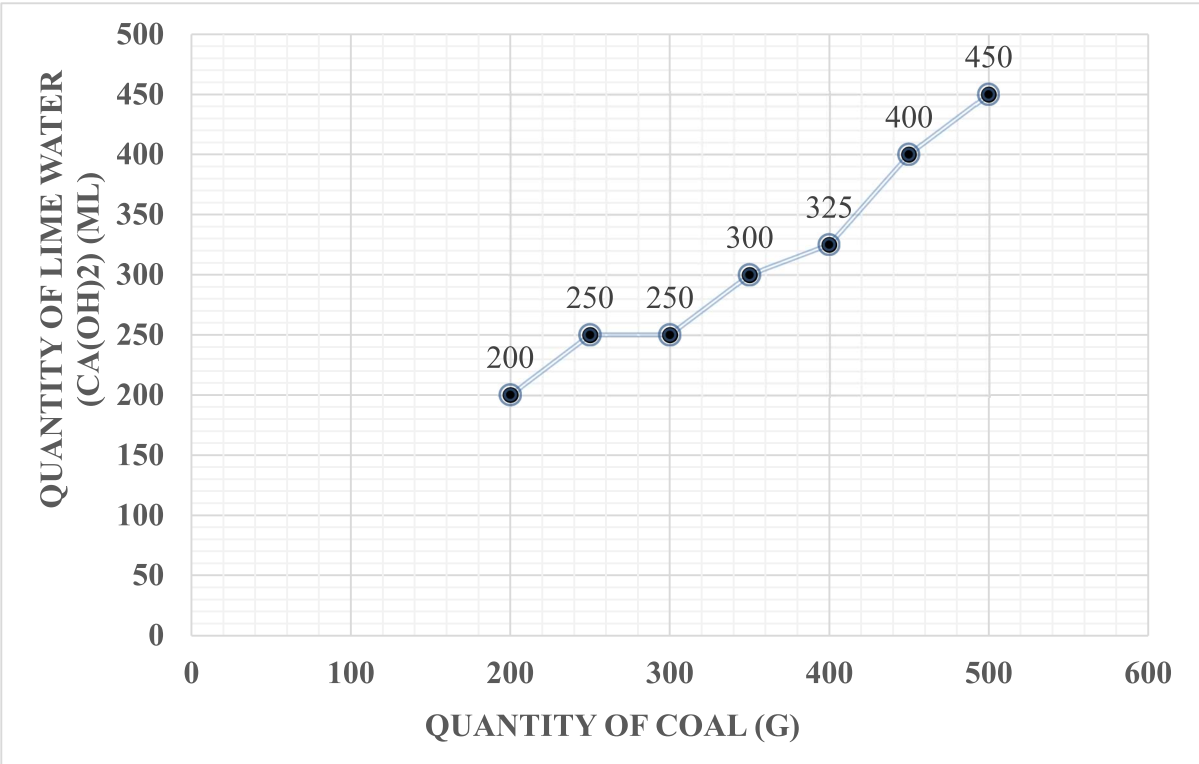


Fig.15 Variation of Ca $(OH)_2$ with Coal.

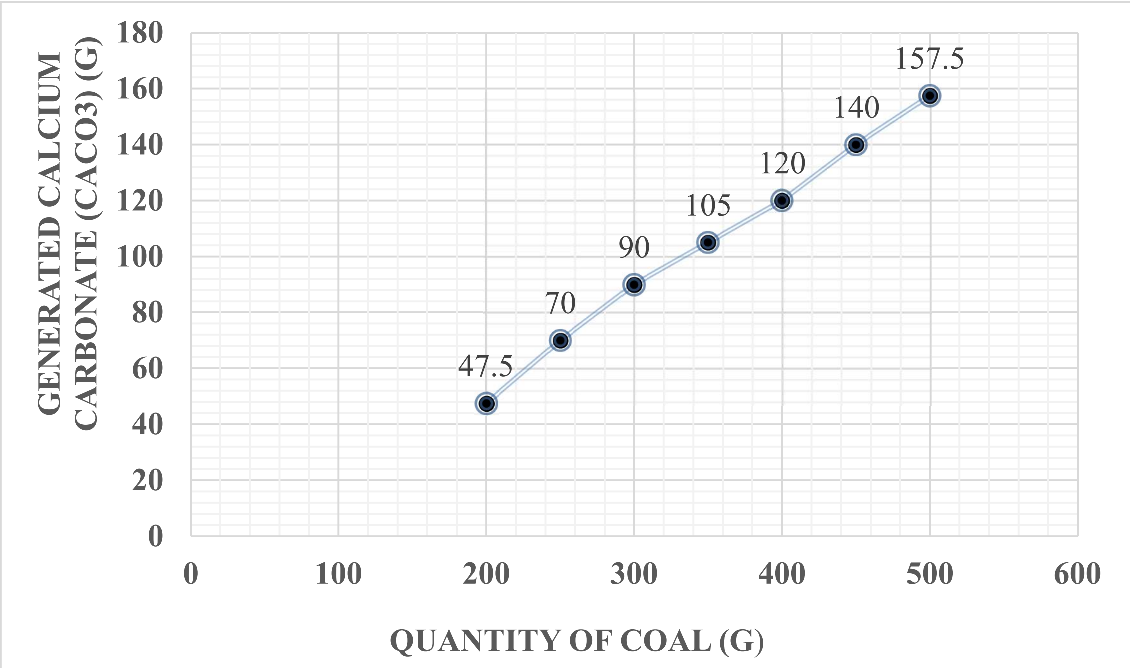


Fig.16 Variation of $CaCO_3$ with Coal.

5. Results And Discussion

We have performed the experiment on carbon capture utilization and storage at Saharsa engineering college Saharsa during Project Works, the results and discussion of these experiences are After detail study and experiment on carbon capture storage and utilization (CCUS) technology we find out a very simple and economical process to separate carbon dioxide from fuel gas which is emitting from the source of carbon dioxide such as cement factory ,steel factory, coal power plant , paper industries , bricks manufacturing plant etc and the process to converting the main and very dangerous gas carbon dioxide which is the main cause of Global Warming into very useful product Calcium Carbonate ($CaCO_3$), which can be used in different sectors for different purpose.

As we see in methodology from figure (13) Colour of lime water changed from color less to milky colour which verified that separated gas is nothing but carbon dioxide. and from the acid test we verified that the ppt is nothing but calcium carbonate. During the experiment period total used material and produced calcium carbonate are shown in table 3.

Table 3: Total Used Material and Produced Calcium Carbonate

Quantity of coal (kg)	Quantity of mono ethanol amine (C_2H_7NO) (ml)	Quantity Of lime water ($Ca(OH)_2$) (ml)	Generated calcium carbonate ($CaCO_3$) (g)
2.4	**500**	**2175**	**50**

When we focus on current sistuation of environment of India particularly in Bihar we obserb that the environment very flucated within last some decades , we obserb that in every season extream weather condtion is occurd , currently we can see the temperture of bihar is 42^{oc} to 44^{oc} occurred even in the month of Aprial and May which is very more . When we try to see the record of WMO (World Metrological Orgnisation) regarding temperture 1 decades back we will see that rararly temperture goes up to 35 to 38oc in the month of June – July which is the month of highest temperture in India partucularly in Bihar. The point of discuss is that why this change occurred , if this changing will continue what will happen after 1 decades .This qustion and this problem attracts all the thinkers and environmentalists. To control this change of envirinment government has also taken many steps like " National Missan for Green India" etc.

Thes all problems are happened due to Greenhouse gases mainly due to excess amount of carbon dioxide present in atmosphere. According WMO the normal percentage of carbon dioxide in atmoshpher should not be more then 400 parts per million (ppm) or 0.04%, according to WMO report 2023 the percentage of carbon dioxide is 420 ppm or 0.042% whighest values in last deceds. "The World Meteorological Organization (WMO) reported that 2023 was the warmest year on record globally, with the global average near-surface temperature at

1.45 ± 0.12 °C above the pre-industrial baseline (1850-1900) (WMO 2023)" Lets seee the veriation of concentration of carbon dioxide with the helf of a graph of last some years provided by WMO. The study of Carbon Capture, Utilization, and Storage (CCUS) reveals promising yet complex outcomes across various applications and technologies. The results highlight that CCUS can significantly reduce CO_2 emissions from major industrial sources, including power plants, cement production, and steel manufacturing, by capturing up to 90% of CO_2 emissions before they reach the atmosphere. Pilot and large-scale projects worldwide demonstrate capture efficiencies ranging between 85% and 95%, depending on the capture technology employed (e.g., post-combustion, pre-combustion, or oxy-fuel combustion).

5.1 Sustainbale Management

This analysis shows that the ideal plant for this application has two specific characteristics; (1) high CO2 purity so that further purification is not required; and (2) large amounts of CO2 available(Zoellelo et al. 2014). Carbon capture and storage (CCS) is considered one of many emerging strategies essential in the global effort to meet the dual challenge of providing affordable and reliable energy while addressing rising greenhouse gas emissions, particularly anthropogenic emissions of carbon dioxide (CO2) into the atmosphere, which are the most significant(Hoffman et al. 2023). For the end consumers of petroleum products, which include end products such as gasoline, fuel oil, aviation kerosene, diesel fuel, lubricants, oils, bitumen, petrochemical raw materials, coke, etc., the quality of the refined oil is important. Therefore, the value of oil products is entirely dependent on the quality of the refining of crude oil(rauth et al. 2023).

Sustainable management of captured carbon dioxide involves long-term storage in geological formations or its conversion into stable, value-added products. It emphasizes minimizing environmental risks, ensuring safe containment, and integrating carbon utilization into circular economy practices. This approach supports climate goals by reducing atmospheric CO_2 while creating economic opportunities. Sustainable management of CCUS (Carbon Capture, Utilization, and Storage) technology involves optimizing capture efficiency, ensuring safe and permanent CO_2 storage, and promoting the use of CO_2 in value-added products. It requires strong regulatory frameworks, continuous monitoring, and integration with renewable energy to minimize the overall environmental impact and support long-term climate goals.

1. Scalability and Flexibility: Designing CCUS systems that can be scaled up or adapted to various industrial settings to meet changing climate and economic needs.
2. Carbon Accounting and Certification: Implementing systems for tracking, reporting, and certifying the amount of CO_2 captured, utilized, and stored to ensure transparency and accountability.
3. Collaboration and Partnerships: Fostering collaboration between governments, industries, and research institutions to share knowledge, reduce costs, and accelerate deployment.
4. Energy Efficiency: Ensuring that CCUS processes are energy-efficient and ideally powered by renewable sources to maximize their climate benefits.
5. Environmental Safeguards: Conducting thorough environmental impact assessments and protecting ecosystems near storage or utilization sites.
6. Job Creation and Skill Development: Promoting green jobs and training programs to build a skilled workforce for CCUS industries.
7. Long-term Vision: Aligning CCUS development with national and global climate targets such as net-zero emissions by mid-century.

6. Conclusions

In an effort to mitigate extreme climate change, slow the progression of global warming, reduce atmospheric CO_2 concentrations, and support environmental goals—including the government's target of achieving zero carbon emissions by 2050—we conducted an in-depth study on Carbon Capture, Utilization, and Storage (CCUS) technology. This research was carried out at Saharsa College of Engineering, Saharsa, Bihar, where a working model was developed and a series of experiments were performed. Based on our comprehensive study, experimental work, and data analysis, we arrived at the following conclusions:

1) A low-cost, small scale experimental setup has been successfully developed for the capture of carbon dioxide (CO_2).
2) The setup is designed to be versatile, making it suitable for both large-scale industrial applications (such as coal-fired power plants, cement factories, and steel industries) and small-scale operations (including rice mills, utensil manufacturing, and brick production units).
3) The captured CO_2 exhibits high purity, eliminating the need for further purification before use.
4) Captured CO_2 can be stored either underground or in suitable cylinders for future utilization.
5) The captured CO_2 has been effectively converted into a valuable product marble powder or calcium carbonate ($CaCO_3$).
6) The synthesized $CaCO_3$ can be utilized across various industries: as a key ingredient in cement manufacturing, a filler and coating pigment in the paper industry, a filler material in plastic production, a building material, and even in the medical field for multiple applications.

7) This technology contributes to mitigating global warming and climate change by preventing the release of 7.67 million tonnes CO_2 per day into the atmosphere.

By taking this step, we are not only contributing to the fight against climate change but also working to protect the environment and preserve the lives of various endangered species—such as the Indian vulture, mynah, sparrow, crow, polar bear, and many others—that are gradually disappearing. These efforts support the broader goal of restoring ecological balance and maintaining a healthy ecosystem.

Carbon Capture, Utilization, and Storage (CCUS) technology represents a vital tool in the global strategy to address climate change. By capturing carbon dioxide emissions from industrial sources and power plants, and either reusing them in industrial applications or storing them securely underground, CCUS can significantly lower greenhouse gas emissions.

This technology is particularly essential in hard-to-abate sectors like cement and steel production, where reducing emissions through traditional methods is more challenging. However, the large-scale deployment of CCUS is not without obstacles. High implementation costs, substantial energy demands, and the need for strict regulatory oversight to ensure safe storage present significant challenges.

Despite these barriers, ongoing research, supportive government policies, and collaboration between the public and private sectors can drive improvements in efficiency and cost-effectiveness. When combined with renewable energy and other sustainable practices, CCUS has the potential to play a crucial role in achieving net-zero emission goals and promoting a more sustainable industrial future.

Conflict of Interest

The authors state that there are no conflicts of interest related to this study.

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References

[1] Agrinier, P., Bonijoly, D., Farret, R., Favre, E., Duong, M. H., Kalaydjian, F., Moisan, F. (2011). The capture, transport, geological storage and re-use of CO2 (CCUS). Strategic road-map (No. INIS-FR--19-0383). Agence de l'environnement et de la maitrise de l'energie-Ademe, 20 Avenue du Gresille, 49000 Angers (France).

[2] Anandarajah, G., Gambhir, A. (2014). India’s CO2 emission pathways to 2050: what role can renewables play? Applied energy, 131, 79-86.

[3] Bruhn, T., Naims, H., Olfe-Kräutlein, B. (2016). Separating the debate on CO2 utilization from carbon capture and storage. *Environmental Science & Policy*, *60*, 38-43.

[4] Chelvam, K., Hanafiah, M. M. (2023). Life cycle assessment of carbon capture, utilization and storage technologies: An analytical review. In IOP Conference Series: Earth and Environmental Science, 1167(1), 012036).

[5] Fetisov, V., Gonopolsky, A. M., Zemenkova, M. Y., Andrey, S., Davardoost, H., Mohammadi, A. H., Riazi, M. (2023). On the Integration of CO2 capture technologies for an oil refinery. *Energies*, 16(2), 865.

[6] Fu, L., Ren, Z., Si, W., Ma, Q., Huang, W., Liao, K., Xu, P. (2022). Research progress on CO2 capture and utilization technology. *Journal of CO2 Utilization*, *66*, 102260.

[7] Godin, J., Liu, W., Ren, S., Xu, C. C. (2021). Advances in recovery and utilization of carbon dioxide: A brief review. *Journal of Environmental Chemical Engineering*, 9(4), 105644.

[8] Guinan, A., Sheriff, A., Basista, E., Shih, C. Y., Hoffman, H., Grant, T. (2023). *Evaluating CCS Cost Options for CO2 Sources in the Central United States* (No. DOE/NETL-2023/4389). National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV, and Albany, OR (United States).

[9] Gulati, A., Rajkhowa, P., Sharma, P. (2017). *Making rapid strides-agriculture in Madhya Pradesh: Sources, drivers, and policy lessons* (No. 339). Working Paper.

[10] Leonzio, G., Shah, N. (2024). Recent advancements and challenges in carbon capture, utilization and storage. *Current Opinion in Green and Sustainable Chemistry*, *46*.

[11] Li, J., Hou, Y., Wang, P., Yang, B. (2018). A review of carbon capture and storage project investment and operational decision-making based on bibliometrics. *Energies*, *12*(1), 23.

[12] Lin, Q., Zhang, X., Wang, T., Zheng, C., Gao, X. (2022). Technical perspective of carbon capture, utilization, and storage. *Engineering*, 14, 27-32.

[13] Liu, E., Lu, X., Wang, D. (2023). A systematic review of carbon capture, utilization and storage: status, progress and challenges. *Energies*, 16(6), 2865.

[14] Mukherji, A., Rawat, S., Shah, T. (2013). Major insights from India's minor irrigation censuses: 1986-87 to 2006-07. *Economic and Political Weekly*, 115-124.

[15] Narain, M. (2007). *Pathways to adoption of carbon capture and sequestration in India: Technologies and policies*, Doctoral dissertation, Massachusetts Institute of Technology.

[16] Orr Jr, F. M. (2018). Carbon capture, utilization, and storage: an update. *Spe Journal*, *23*(06), 2444-2455.

[17] Osman, A. I., Hefny, M., Abdel Maksoud, M. I. A., Elgarahy, A. M., Rooney, D. W. (2021). Recent advances in carbon capture storage and utilization technologies: a review. *Environmental Chemistry Letters*, *19*(2), 797-849.

[18] Panda, S. (2019). *Monitoring Soil Moisture of Indian Subcontinent Covering Entire Kharif Season (2018) Using SMAP Data*, Doctoral dissertation, Department of Farm Engineering Institute of Agricultural Sciences Banaras Hindu University Varanasi.

[19] Rosa, L., Sanchez, D. L., Realmonte, G., Baldocchi, D., D'Odorico, P. (2021). The water footprint of carbon capture and storage technologies. *Renewable and Sustainable Energy Reviews,* 138, 110511.

[20] Shaw, R., Mukherjee, S. (2022). The development of carbon capture and storage (CCS) in India: A critical review. *Carbon Capture Science & Technology*, 2, 100036.

[21] Shih, C. Y., Morgan, D., Liu, G., Cunha, L. (2024). *Optimizing Carbon Capture, Transport, and Storage: Overcoming Challenges with Machine Learning and Cost-Benefit Analysis*. National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV, and Albany, OR (United States).

[22] Shreyash, N., Sonker, M., Bajpai, S., Tiwary, S. K., Khan, M. A., Raj, S., Biswas, S. (2021). The review of carbon capture-storage technologies and developing fuel cells for enhancing utilization. *Energies,* 14(16), 4978.

[23] Singh, A. K., Mendhe, V. A., Garg, A. (2006). CO2 storage potential of geologic formations in India. In *Proceedings of the 8th Greenhouse Gas Technology Conference, Trondheim, Norway* ,19-22.

[24] Singh, U. (2013). Carbon capture and storage: an effective way to mitigate global warming. *Current Science*, 914-922.

[25] Song, D., Jiang, T., Rao, C. (2022). Review of policy framework for the development of carbon capture, utilization and storage in China. *International Journal of Environmental Research and Public Health*, 19(24), 16853.

[26] Summers, W. M., Herron, S. E., Zoelle, A. (2014). *Cost of capturing CO2 from industrial sources* (No. DOE/NETL-2013/1602). National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV, and Albany, OR (United States).

[27] Sun, L., Dou, H., Li, Z., Hu, Y., & Hao, X. (2018). Assessment of CO2 storage potential and carbon capture, utilization and storage prospect in China. *Journal of the energy institute*, *91*(6), 970-977.

[28] Teske, S. (2019). *Achieving the Paris climate agreement goals: Global and regional 100% renewable energy scenarios with non-energy GHG pathways for+ 1.5 C and+ 2 C*, (p. 491). Springer Nature.

[29] Van Alphen, K., Noothout, P. M., Hekkert, M. P., Turkenburg, W. C. (2010). Evaluating the development of carbon capture and storage technologies in the United States. *Renewable and Sustainable Energy Reviews*, *14*(3), 971-986.

[30] Wigley, T. M. L. (1983). The pre-industrial carbon dioxide level. *Climatic change*, 5(4), 315-320. https://doi.org/10.1007/BF02423528

[31] Zhan, J., Chen, Z., Zhang, Y., Zheng, Z., Deng, Q. (2020). Will the future of shale reservoirs lie in CO2 geological sequestration? *Science China Technological Sciences*, *63*(7), 1154-1163.

[32] Zhang Xian, Z. X., Fan JingLi, F. J., Wei YiMing, W. Y. (2013). Technology roadmap study on carbon capture, utilization and storage in China. Chiang, P. C., Pan, S. Y., Chiang, P. C., & Pan, S. Y. (2017). Post-combustion carbon capture, storage, and utilization. *Carbon dioxide mineralization and utilization*, 9-34.

[33] Zhang, X., Fan, J. L., Wei, Y. M. (2013). Technology roadmap study on carbon capture, utilization and storage in China. *Energy Policy*, *59*, 536-550.