JOURNAL OF BIOCHEMICAL SCIENCES
Jan-Mar 2024, VOL. 1, ISSUE 1, pp. 8-15
https://doi.org/10.61577/jbs.2024.100003

RESEAPRO JOURNALS

REVIEW

OPEN ACCESS

Recent trends in carbon sequestration technique

Sakshi Tripathi[1], R.B. Lal[2], Abhilasha Singh Mathuriya[2], R.P. Rastogi[2] and B.S. Sandeepan[2]

[1]Department of Environmental Science, Institute of Bioscience and Biotechnology, Chhatrapati Shahu Ji Maharaj University, Kanpur, India
[2]Ministry of Environment, Forest and Climate Change, New Delhi, India

ABSTRACT

The current review aims to explore potential methods for reducing carbon emissions based on recent developments in carbon sequestration. Carbon dioxide (CO_2) emissions are widely recognized as one of the primary *Greenhouse gases* (GHGs) contributing to global climate change. Carbon sequestration plays a crucial role in effectively mitigating carbon emissions through various approaches such as establishing green areas within industrial zones, minimizing waste generation, promoting renewable energy generation, conserving natural resources, practicing energy conservation, and implementing solid waste reuse, recycling, and recovery methods. Other techniques involve capturing and sequestering carbon using methods like pre-combustion and post-combustion CO_2 capture, employing membrane separation, adsorbent-based processes, amine scrubbing, cryotechnology, direct gas-solid carbonation, direct aqueous carbonation, and indirect carbonation. Furthermore, in addition to this abiotic carbon sequestration, diatoms have recently been recognized as some significant contributors to carbon sequestration methods, diatoms have been as to carbon sequestration, particularly in oceanic ecosystems where they serve as primary producers. Thus, this review provides an overview of the main techniques employed in carbon sequestration, which contribute to the reduction of global carbon emissions and address the larger issue of climate change.

KEYWORDS

Global climate; Carbon dioxide; Greenhouse gases (GHGs); Carbon sequestration; Diatoms

ARTICLE HISTORY

Received 15 October 2023; Revised 8 February 2024; Accepted 20 February 2024

Introduction

The utilization of fossil fuels for energy production, driven by industrial development and increasing energy consumption, leads to the release of significant amounts of carbon dioxide (CO_2) into the environment. It is projected that coal-based primary energy generation will contribute to annual CO_2 emissions of 38,749 Mt CO_2 and reach 3,976 Mtoe by 2030 [1]. Extensive efforts are being made to mitigate the impact of GHG emissions on climate systems across various industrial sectors. According to the Intergovernmental Panel on Climate Change (IPCC), CO_2 accounts for 65% of total GHG emissions [2]. The production and processing of cement are responsible for 5%-7% of anthropogenic CO_2 emissions in the building and construction sector [3]. In the context of developing a circular economy, it is important to consider climate change and leverage it as a source of inspiration and operationalization. The emphasis on resource efficiency implies the adoption of nature-based approaches to combat climate change. Policies based on natural solutions have gained popularity due to their significant environmental, social, and economic benefits. As global climate targets are still far from being achieved, the concept of a circular economy should be harnessed to drive nature-based policies. Concrete and comprehensive efforts utilizing all available options need to be implemented. Ongoing research explores the potential of fruit farming, as a land industry, in mitigating climate change. In this regard, an analysis was conducted to assess the economic value of CO_2 sequestration ecosystem services provided by tree-based systems [4]. Carbon sequestration is the process of removing and storing carbon that would otherwise be released or remain in the atmosphere and plays a vital role. It involves halting carbon emissions before they enter the environment and directing them to a secure storage area. Alternatively, atmospheric carbon can be captured from the atmosphere or industrial sources and stored through carbon sequestration, which comprises two steps: (I) capturing CO_2 resources and (II) storing it.

The lower concentration of CO_2 in the atmosphere compared to N_2 and O_2 implies the cost of CO_2 capture is expected to be higher. To fully comprehend the scientific and technical aspects of carbon sequestration solutions and their potential, thorough investigations are necessary. Carbon sequestration serves as a fundamental method for reducing carbon emissions from fossil fuels. Given the need to lower atmospheric CO_2 concentration by addressing significant CO_2 emissions, a range of carbon management strategies become essential. Integrating carbon sequestration with enhanced energy efficiency and fuel decarbonization is crucial, as it allows for the sustainable and extensive utilization of fossil fuels while substantially mitigating atmospheric CO_2 emissions. Current projections indicate that there will be an adequate supply of fossil fuels, including conventional oil and gas, coal, and unconventional fuels like heavy oil and tars, to meet global energy demand for the next century. The short-term dynamics of the natural carbon cycle are dynamic, with the acceleration of CO_2-emitting activities being counterbalanced by the acceleration of natural systems

*Correspondence: Dr. R.B. Lal, Ministry of Environment, Forest and Climate Change, New Delhi, India, e-mail: rb.lal@nic.in

that store CO_2. Artificial extraction and sequestration of carbon occur through the combustion of fossil fuels without contributing to atmospheric carbon emissions. To reduce the overall positive carbon flux to the atmosphere, new carbon sequestration techniques are being developed, and the efficiency of existing methods are improving [5].

Mitigating global warming and climate change can be achieved by reducing human-induced CO_2 emissions into the atmosphere [6]. According to the IPCC [2], there are various methods available for lowering emissions, including biological storage, mineral storage, oceanic storage, and geological storage [7]. Among these methods, "geological storage" is widely recognized as the most commonly used approach for CO_2 storage. It involves injecting the gas into underground geological formations such as depleted oil and gas reservoirs, coal seams, salt caverns, and saline aquifers [8].

This review paper aims to review various technologies used in carbon sequestration in mitigating the impact of carbon dioxide (CO_2) emissions resulting from the utilization of fossil fuels for energy production. The novelty lies in the comprehensive examination of carbon sequestration techniques, including both established methods and emerging technologies, with a focus on their scientific and technical aspects. This paper contributes to the ongoing discourse on Carbon capture and storage (CCS) by providing a comprehensive examination of various methods, including membrane separation, molecular sieves, and desiccant adsorption, employed to address the challenge of CO_2 emissions from fossil fuel consumption. The novelty of this work lies in its emphasis on the scientific and technical aspects of these methods, exploring their potential, limitations, and economic implications in the fight against climate change.

Carbon flux

The exchange of carbon among Earth's carbon reservoirs, including the ocean, atmosphere, land, and living organisms, is known as carbon flux. It is measured in Gt C/yr (giga tonnes of carbon per year) [9]. These methods provide an increasingly widespread and continuous temporal record of terrestrial carbon flux across different regions. Specifically, the Eddy covariance (EC) technique is used to measure CO_2 flux at specific sites [10]. These techniques enable continuous temporal coverage of terrestrial carbon flux across the continent, with an expanding number of locations being monitored [10,11]. The analysis of EC data, which encompasses temporal changes and environmental factors, is crucial for studying the exchange of CO_2 between the atmosphere and terrestrial ecosystems [12]. Carbon balance research has made significant advancements at both large and small scales, encompassing vast continents (> 106 km², e.g., global inverse modeling) and smaller areas (less than 1-3 km², e.g., EC measurements). However, there is a scarcity of approaches for estimating CO_2 emissions and sinks at an intermediate scale between the continental and local levels. Climate change can significantly impact the carbon cycle in various regions [13,14]. Another effective strategy for reducing carbon emissions involves modeling ecological variability and atmospheric dispersion through an integrated boundary layer model for the ecosystem [15].

Carbon footprint

The carbon footprint refers to the overall amount of carbon dioxide (CO_2) emissions associated with the activities of an individual, organization, or country. It encompasses direct emissions from the combustion of fossil fuels for heating, transportation, and power generation, as well as emissions resulting from the production and consumption of various products and services. In addition to CO_2, the carbon footprint assessment also considers other greenhouse gases such as methane, nitrous oxide, and chlorofluorocarbons [16]. There are eight categories of carbon footprint analysis (Figure 1).

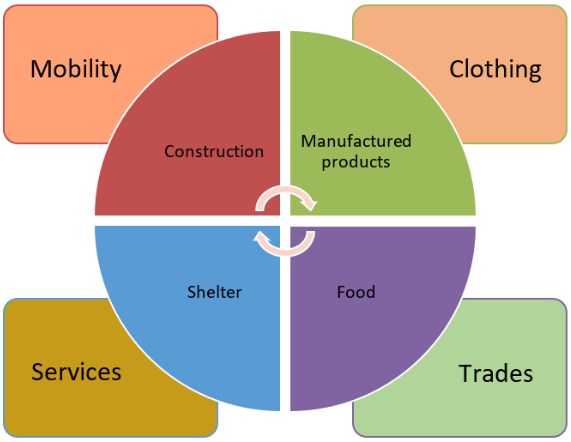

Figure 1. Categories of carbon footprint analysis.

Carbon footprints and carbon absorptions play a vital role in providing a methodological foundation for informed decision-making by policymakers. The widespread utilization of carbon footprints, based on up-to-date data, should be encouraged or regulated as necessary. Carbon footprints empower consumers to adopt climate-friendly behavior and aid the government in designing effective regulations that avoid incentivizing improper product choices. Businesses can employ carbon footprints to minimize their exposure to carbon-related costs and showcase their positive contributions. In recent years, there has been a growing interest in comprehending the factors driving emissions through carbon pathways and exemplifying carbon fluxes at various scales [17]. The concept of a carbon footprint pertains to identifying the source, quantity, and removal of GHG emissions resulting from both on-farm and off-farm activities, with the objective of reducing GHG emissions and enhancing GHG sinks in a specific system [18].

Analysis of carbon footprint

Carbon footprints can be calculated for different functional units and sizes using various methodologies. The three main approaches for determining carbon emissions are Input-output (IO) analysis, Life-cycle assessment (LCA), and IO-LCA. Significant progress has been made in establishing standards for carbon footprint assessment, such as ISO14064, GHG Protocol, and PAS2050. The adoption of these regulations has led to a substantial reduction in global carbon emissions [19].

According to the IPCC Guidelines, a "carbon footprint" is defined as the representation of an organization's activities' climate impact, measured in terms of the total amount of GHG generated and expressed in CO_2e units.

To calculate GHG emissions for each source, the following formula can be used:

ADS × EFS (IPCC)

https://doi.org/10.61577/jbs.2024.100003

Where GHG emissions from a specific source are determined by multiplying the source's Activity data (ADS), with its corresponding GHG Emission factor (EFS). The activity data represents the quantity of the source's activity (e.g., liters of petrol or kWh of electricity), while the emission factor converts this activity data into GHG emissions [2].

When calculating total GHG emissions, the carbon footprint is expressed in carbon dioxide equivalent (CO_2e) units. This unit represents the same amount of CO_2 emissions as other greenhouse gases that contribute to global warming [20].

Statistics of carbon footprint

In India, industries play a significant role in energy-related carbon dioxide (energy-CO_2) emissions, accounting for 25% of the overall emissions, and secondly, in power generation [21]. Energy-related CO_2 emissions primarily originate from industrial activities, with power generation being the only sector contributing to a larger proportion of the total emissions. In 2018, India's total energy-related emissions reached 2,251 Mt CO_2. Industries accounted for 53% of these emissions, while power generation contributed 25%. Transport and residential sources were the second and third largest contributors, accounting for 14% and 4% of the overall emissions, respectively. The remaining 4% of emissions came from commercial and agricultural sources as well as other industries.

However, the categorization of industries in India's GHG emissions inventory differs significantly. The ISIC classification system classifies emissions under headings such as mining, textiles, leather, non-ferrous metals, iron and steel, and non-ferrous metals mining. According to the International Standard Industrial Classification of all Economic Activities (ISIC), cement and fertilizers should be considered under chemicals and non-metallic minerals. However, the country's data presents non-metallic mineral and cement emissions separately. Emissions from fertilizers and chemicals are also tracked separately in a similar manner [22].

Industrial pollution has grown at a rapid pace over the past few years. Table 1 illustrates the growth of CO_2 emissions from energy use, which increased from 228 Mt CO_2 in 2000 to 396 Mt CO_2 in 2016. Process CO_2 emissions also saw an increase from 73 Mt CO_2 in 2000 to 166 Mt CO_2 in 2016. Consequently, India's industrial sector overall emitted more CO_2, rising from approximately 300 Mt CO_2 in 2000 to around 560 Mt CO_2 in 2016. It is worth noting that an important portion of industrial emissions is not attributed to any specific sector in the official data. For our sectoral analysis, we use data from the Global Trade Study Project (GTAP), which provides comprehensive data for all countries, including India [23].

Table 1. Industry CO_2 emissions in India. Data source: MoEF (2012), MoEFCC (2015, 2018, 2021) [24].

Mt CO_2	2000	2010	2014	2016
Total CO_2 Emissions in India	1024.8	1574.4	1997.9	2231
Energy Use Related Emissions in India (Fuel)	952.2	1441.9	1844.7	2064.8
Energy Use in Industry ("Industry-Fuel")	228.2	299.2	350.2	395.9
Iron and Steel (Fuel)	52.4	95.5	153.9	134.7
Cement (Fuel)	39.7	40.5	46.9	53.5
Non-Ferrous Metals (Fuel)	1.9	1.9	1.7	7.7
Chemicals (Fuel)	34.5	7.9	2	2
Pulp and Paper (Fuel)	5.3	6.7	3.9	2.6
Unspecified/Other Small Items (Fuel)	94.4	146.7	141.8	195.4
Industrial Processes and Product Use ("Industry-Process")	72.6	132.5	153.2	166.2
Mineral Products	53.6	104.5	126.9	135.5
Cement (Process)	44.1	83.8	115.3	106.6
Chemical Industry	15.8	19.5	18.5	21.3
Ammonia (Process)	11.1	12.6	10.2	11.5
Ethylene (Process)	3.3	5.1	6.2	7.6
Metal Production	2.5	6.8	5.7	7.2
Ferro Alloys (Process)	1.5	3.7	2.5	2.7
Aluminum (Process)	1	3.1	3.1	4.5
Total Industry Emissions (Fuel+Process)	300.8	431.7	503.4	562.1

Goals of carbon sequestration

The 26th United Nations Climate Change Conference of the Parties established the goal of achieving a net-zero economy through national efforts. The focus of the conference was the Paris Rulebook, which comprises a set of regulations discussed among the participating countries. To achieve this objective, governments, national sectors, and financial institutions must collaborate on a global scale [25]. The 26th United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP26) took place in Glasgow, United Kingdom. During the conference, the Indian government emphasized and conveyed the concerns of developing nations. India also presented the five main elements

https://doi.org/10.61577/jbs.2024.100003

(Panchamrit) of its climate achievement, which include the following: By 2030, India aims to have a non-fossil energy capacity of 500GW and renewable energy, fulfilling 50% of the nation's energy requirements. The country also aims to reduce carbon emissions by one billion tonnes by 2030, lower the economy's carbon intensity by 45% compared to 2005 levels, and ultimately achieve net-zero emissions by 2070 [26].

Carbon mitigation measures and techniques

The world must implement noteworthy mitigation measures to effectively address the issue of high carbon emissions, especially in urban areas where industries are concentrated. Rapid industrialization is a major contributor to the substantial release of carbon into the atmosphere.

To mitigate these emissions, industries should consider the following actions:

- Developing green belts within industrial areas
- Minimizing waste generation
- Conserving energy
- Preserving natural resources
- Implementing solid waste reuse, recycling, and recovery practices

One approach to mitigate and adapt to climate change in buildings is by installing green walls and rooftops [27]. This strategy helps reduce carbon emissions and provides adaptation benefits.

In the transportation sector, reducing and adapting to climate change can be achieved through various strategies, including promoting car-sharing, enhancing vehicle efficiency, transitioning to electric transportation, and encouraging the use of public transportation [28]. These measures contribute to the reduction of carbon emissions and support climate change adaptation efforts in the transportation sector.

Techniques for mitigating carbon emission

Production of renewable energy

Utilizing hydrogen fuel for energy generation is regarded as one of the most effective solutions due to its CO_2-free nature. Hydrogen possesses several advantageous properties at Normal temperature and pressure (NTP). These include a wide flammability limit by volume (4%-75%), low ignition energy (0.02 mJ), and low density (0.083 kg/m^3) [1,29]. In terms of production, primary energy sources such as fossil fuels (e.g., natural gas, coal) can be utilized in the short and medium term [29,30].

Capturing of carbon and sequestration

Carbon capture and sequestration (CCS) is an advanced renewable energy technology that aims to prevent or reverse CO_2 emissions into the atmosphere by directing carbon towards long-term storage. The process involves capturing and storing CO_2 at its source before it is released into the environment [1]. CCS serves as a mid-term solution for the sustainable use of fossil fuels and the expansion of renewable energy sources [31]. There are two primary types of CCS: pre-combustion CCS, which involves capturing carbon during the fuel preparation stage before it is burned for energy production, and post-combustion CCS, which captures CO_2 from flue gas and other combustion-related processes., enhancing CO_2 uptake in soil, plants (such as through tree planting initiatives), or the ocean through methods like iron fertilization can also contribute to CO2 reduction efforts.

Pre combustion CCS

The pre-treatment process involves coal gasification in a low-oxygen gasifier, resulting in syngas primarily composed to further enhance the production of H_2 and convert CO gas to CO_2; the syngas undergo a water-gas shift reaction with steam. during the steam-methane reforming process, both CO and CO_2 are generated. Due to the high CO_2 concentration in the H_2/CO_2 fuel gas mixture, the separation of CO_2 becomes necessary. Subsequently, H_2 is combusted in the atmosphere, resulting in the production of mostly N_2 and water vapor, effectively removing CO_2 from the environment [32,33].

Post-combustion CCS

The process of capturing and sequestering CO_2 from flue gas before it is released into the atmosphere is known as post-combustion CCS. It is recommended to retrofit the existing operational power plant currently with post-combustion technology. Although post-combustion CCS technology has demonstrated its effectiveness [34], it imposes a significant parasitic load to enable the capture unit to raise the CO_2 concentration. This is necessary due to the low CO_2 concentration in the combustion gas and the associated costs (95.5% or more) for transportation and storage. In addition to CO_2 capture, current post-combustion technology requires the purification of N_2, NO_X, and SO_2 byproducts before CO_2 capture [35].

CCS technology development for CO_2 capture

Emerging technologies refer to a range of products and processes that have demonstrated significant improvements in efficiency and cost beyond current levels of knowledge and technological development, whether in laboratory settings or practical applications. Various methods for CO_2 separation and capture include microbial/algal systems, absorption, adsorption, cryogenics, membrane separation, and absorption [34,36].

Membrane separation technique

In the process of membrane separation, specially designed membrane sieves are utilized to separate molecules based on their molecular size. The effectiveness of CO_2 separation has been demonstrated through various experiments involving the separation of CO_2, H_2S, and H_2O from CO, CH_4, air, and gas mixtures [37,38]. Membrane technologies include inorganic membranes, mixed matrix membranes, hollow fiber gas-liquid membrane contactors, Polymer gas permeable membranes (PGPM), Facilitated transport membranes (FTM), and others. While polymer membranes generally exhibit 5-10 times lower selectivity compared to inorganic membranes, they are cost-effective for industrial applications. In contrast, inorganic membranes offer mechanical, chemical, and thermal durability, making them suitable for high-temperature CO_2 separation processes. Further research and development efforts are required to enhance reproducibility, dependability, and affordability [38].

The advancement of membrane-based technologies aim to support sustainable systems with minimal CO_2 emissions. Membrane separation methods involve non-dispersive absorption, porous membranes, gas permeation, and a supported liquid membrane [39]. Achieving the necessary CO_2 capture and purity (with 80% CO_2 in the permeate flow) can be

https://doi.org/10.61577/jbs.2024.100003

challenging with commercial membranes that have up to 50% selectivity [40]. Membrane separation is an attractive option due to its affordability, minimal waste generation, and its applicability in various carbon sequestration strategies.

System based on adsorbent

An adsorbent is capable of adsorbing compounds onto its surface through intermolecular interactions. It possesses a surface area and is often porous. This allows it to physically or chemically retain other molecules on its surface, known as the adsorbate. To regenerate the adsorbent beds and release the adsorbate, pressure swings, temperature swings, and washing procedures are employed [34].

Two types of solid adsorbents are commonly used: amine-based and alkali (earth) metal-based adsorbents [41]. The carbonate system utilizes the ability of soluble carbonates to combine with CO_2, forming bicarbonate, which can be heated to release CO_2 and convert it back into carbonates. A study found that a K2CO3-based system with a Piperazine (PZ) catalyst, the K_2CO_3/PZ system (5 molar K; 2.5 molar PZ), exhibited a 10%-30% faster absorption rate compared to a 30% Mono-ethanolamine solution (MEA) [42,43].

Converting industrial wastes from one form to another is complex, as each waste has its unique characteristics. For example, cement waste contains a significant amount of CaO, which can be utilized as a CO_2 adsorbent. An analysis of Underground coal gasification (UCG) technology reveals that it is an effective method for producing low-carbon fuel by capturing CO_2 at the gasification site itself [44].

Scrubbing with amines

Amine-based devices are capable of capturing CO_2 from flue gas by reacting with CO_2 and producing water-soluble molecules [43]. One commonly used technology for this purpose is Monoethanolamine (MEA) scrubbing, which employs a chemical absorption mechanism using MEA as the solvent to scrub CO_2 from combustion exhaust. In this process, the flue gas comes into contact with the MEA solution and undergoes absorption at approximately 38 °C. The CO_2-rich MEA solution is then heated to 150 °C in a stripper to release almost pure CO_2. Although other amine compounds like diglycolamine (DGA), diethanolamine (DEA), triethanolamine (TEA), and methyl diethanolamine (MDEA), can also be used for scrubbing, MEA has proven to be the most efficient, achieving over 90% CO_2 absorption [45,46].

The MEA scrubbing process has some challenges as it requires vital equipment and a large amount of renewable energy to release CO_2 from the MEA solution, making it relatively inefficient. To overcome this, solar systems can be used to provide regenerated thermal energy., Improvements in system condensation and design can help reduce capital costs and enhance energy integration [43]. To address the energy-intensive drawbacks of MEA cleaning, a reactive hydrothermal liquid phase densification (rHLPD) method can be utilized, which eliminates the need for a high-temperature furnace to cure monolithic materials [47]. This offers an alternative approach to avoid the energy-intensive aspects of the process [47].

Separation using cryotechnology

Cryogenic separation is an essential procedure for CO_2 removal, requiring distillation at very low temperatures and pressures. During this process, flue gas is directed onto a cooling medium. As the flue gas containing CO_2 cools to a sublimation temperature (100-135 °C), solidified CO_2 is separated from other gases. CO_2 recovery from flue gas can reach up to 90-95 percent [46].

Two cryogenic separation techniques are employed: internal cooling flash separation and distillation column separation. However, distillation is an energy-intensive process, demanding approximately 600-660 kWh per tonne of CO_2 recovered due to its extremely low temperature and high pressure [46,48]. Various carbon separation and capture systems can be applied, each with unique properties. Selecting the most suitable technology should be based on how well it aligns with specific needs and requirements.

Mineral sequestration of CO_2

There are two methods for mineral sequestration: direct carbonation and indirect carbonation [49]. Direct carbonation involves two phases: the gas phase and the aqueous phase. In the gas phase, CO_2 reacts with minerals like rocks, both in situ and ex situ, to form carbonates. In the aqueous phase, simple carbonation occurs, and additives can enhance the carbonation process [50]. On the other hand, indirect carbonation follows a different approach, where the reactive mineral ions of the feedstock dissolve first, and then the dissolved mineral ions undergo carbonation in two distinct reactors [51].

Direct carbonation

Direct carbonation is a fundamental approach to mineral sequestration. It involves carbonating a suitable feedstock, such as mineral sources or a solid residue rich in calcium (Ca) or magnesium (Mg), in a single step within the same reactor [52]. Minerals are extracted, and dissolved minerals are then carbonated during this process.

Direct gas-solid carbonation

Direct aqueous carbonation is a more complex method of mineral sequestration than gas-solid mineral sequestration. In this reaction, gaseous CO_2 reacts with mineral oxides under specific pressure and temperature conditions [53,54]. Integrating the carbonation process with mining operations may help reduce costs and energy requirements, and it could potentially lead to improved rates and purer mineral extraction. However, direct gas-solid carbonation faces challenges due to sluggish reaction rates caused by thermodynamic restrictions, leading to limited research in this area [49].

Direct aqueous carbonation

Direct aqueous mineral carbonation is currently the most efficient technology for CO_2 sequestration, yielding high carbonation levels [6,55]. Although this method can be costly for widespread CO_2 sequestration, it is still frequently employed in ex-situ applications. On-site direct aqueous carbonation, including CO_2 reaction with rock samples, is also feasible. By controlling the composition of the input gas and enhancing carbonation efficiency, it is possible to reduce porosity loss and improve permeability [56].

In addition to intentional carbonation, direct aqueous carbonation occurs naturally during weathering when waste ash piles are exposed to atmospheric CO_2 [55]. By-products, residues, and industrial waste often exhibit faster reactivity than native minerals [52,57]. The characteristics and composition of

https://doi.org/10.61577/jbs.2024.100003

the residues are influenced by changes in process variables such as temperature and pressure [58]. Carbonation efficiency ($NaHCO_3$) in direct aqueous carbonation can be enhanced by incorporating additives like sodium chloride (NaCl) and sodium carbonate [54]. Miao et al. used a Circulating fluidized bed (CFB), an advanced clean combustion facility that has seen rapid development in recent years. CFB offers distinct advantages over conventional pulverized coal boilers, including high combustion efficiency, broad fuel adaptability, and significantly reduced NOx emissions attributed to its lower combustion temperature [59].

Indirect carbonation

The mineral carbonation process utilizes the indirect carbonation method, which involves removing the reactive component (e.g., Ca or Mg) from the minerals as an oxide or hydroxide before reacting with CO_2 to form stable carbonates in the subsequent stage [51,60,61]. The extraction of magnesium oxide (MgO) or magnesium hydroxide ($Mg(OH)_2$) is carried out at atmospheric pressure, followed by a second carbonation phase at higher temperatures of 500 °C and 20 bars of pressure [62]. $Mg(OH)_2$ exhibits faster carbonation compared to MgO.

By using the carbonation reaction represented by the equation below, Mg(OH)2 can accelerate the overall process:

$$Mg(CO_3)_2(s) + H2O\ Mg(OH)_2(s) + CO_2 \quad (1)$$

Acetic acid is employed to accelerate the carbonation process, enhancing the extraction of calcium from calcium-rich material [58]. However, the use of additives like acetic acid may also lead to the leaching of other materials, including heavy metals, during the Calcium extraction phase. This can result in the formation of impure carbonate and create environmental hazards [55,63].

Diatoms as a carbon sequester

By combining CO_2 sequestration through photosynthetic organisms with bioprocessing and biomanufacturing for value addition, this method of carbon storage can be made more environmental friendly. The precursors of present-day cyanobacteria were discovered to produce molecular oxygen through oxygenic photosynthesis over 2.7-3.7 billion years ago [64]. Microalgae exhibit remarkable solar energy conversion efficiency, reaching up to 3% in reality (biomass productivities of up to 146 tdw ha-1y-1 in small-scale cultivations and 60-75 tdw ha-1y-1 in mass cultivations), equivalent to theoretical efficiencies of 8-10% of solar energy (biomass productivities of 280 tonne dcw ha-1y-1) [65,66]. Notably, microalgae trap CO_2 faster than trees [67].

While several enterprises have succeeded in producing biomass and high-value compounds like pigments (carotene, astaxanthin, phycocyanin), and omega-3 fatty acids, large-scale microalgal cultivation for biofuels has been constrained due to concerns about its sustainability and economic feasibility (docosahexaenoic acid and eicosapentaenoic acid). Many companies power their production plants with sustainable energy sources, including solar energy and geothermal energy (Algalif-Iceland).

Carbon typically constitutes between 40% and 60% of the dry weight of microalgal cells. With current biomass productivities in the range of 60-140 tonne dcw ha-1y-1 for a carbon content of 50% dcw, the amount of carbon that could be fixed would be 30-70 tonne ha-1y-1. This translates to a potential CO_2 fixing capacity per hectare of between 100 and 250 tonnes of CO_2. Although it would require large-scale cultivations, every little bit contributes toward the overall aim, justifying the development of designs that would maximize the potential for microalgal CO_2 sequestration [68]. Ahmad et al. outlined the role of diatoms in CO_2 mitigation and the diatom species involved in bio sequestrating of CO_2. Diatoms can serve as pathways toward carbon footprint reduction and CO_2 mitigation in providing a solution to environmental and climate issues [69].

Conclusions

The demand for energy in industrial and transportation activities is predominantly met by fossil fuels such as diesel, gasoline, natural gas, and coal, which release CO_2 into the atmosphere as a greenhouse gas. It is projected that by 2030, coal's primary energy output will increase to 3976 Mtoe, resulting in annual CO_2 emissions of 38749 Mt CO_2. Membranes, molecular sieves, and desiccant adsorption methods are also utilized. To address this challenge, various methods like membrane separation, molecular sieves, and desiccant adsorption are utilized for CO_2 removal. Membrane separation processes have shown promise in removing a substantial amount of CO_2, while amine scrubbing can eliminate over 85% of CO_2 from flue gas produced by fossil fuel-based generators. Currently, more than 50 CCS initiatives are underway worldwide, although large-scale demonstration projects might be influenced by the unpredictability of the global climate change discussion. CO_2 isolation remains a complex task that requires careful consideration of economics. Tailoring CCS technologies to specific regional conditions and combining them with appropriate technologies can lead to cost savings and viable solutions. Collaboration between policymakers, the environmental community, and the scientific community is crucial in advancing CCS applications. Raising awareness among the general public about the capabilities and limitations of CCS techniques is essential for their successful implementation. Future research in the realm of carbon sequestration techniques should focus on several key directions to advance our understanding and enhance the efficacy of these methods. Firstly, there is a need for in-depth investigations into the scalability and long-term effectiveness of emerging technologies such as membrane separation, molecular sieves, and desiccant adsorption. Rigorous assessments of these methods under various operational conditions and across different industrial sectors will provide valuable insights into their applicability and limitations. Researchers should explore innovative approaches to optimize the economic feasibility of carbon sequestration, considering regional variations and tailoring technologies to specific contexts. Integration studies that combine carbon sequestration with other sustainable practices, such as enhanced energy efficiency and renewable energy sources, could offer comprehensive solutions. Furthermore, understanding the environmental and social impacts of large-scale carbon sequestration initiatives is crucial for responsible and ethical implementation.

Disclosure statement

No potential conflict of interest was reported by the authors.

https://doi.org/10.61577/jbs.2024.100003

RESEAPRO JOURNALS

References

1. Salvi BL, Subramanian KA. Sustainable development of road transportation sector using hydrogen energy system. Renew Sustain Energy Rev. 2015;51:1132-1155. https://doi.org/10.1016/j.rser.2015.07.030
2. Metz B, Davidson O, De Coninck HC, Loos M, Meyer L. IPCC special report on carbon dioxide capture and storage. Cambridge: Cambridge University Press; 2005. https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/
3. Gupta S. Carbon sequestration in cementitious matrix containing pyrogenic carbon from waste biomass: a comparison of external and internal carbonation approach. J Build Eng. 2021;43:102910. https://doi.org/10.1016/j.jobe.2021.102910
4. Bithas K, Latinopoulos D. Managing tree-crops for climate mitigation. An economic evaluation trading-off carbon sequestration with market goods. Sustain Prod Consum. 2021;27:667-678. https://doi.org/10.1016/j.spc.2021.01.033
5. Reichle D, Houghton J, Kane B, Ekmann J. Carbon sequestration research and development. Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States); National Energy Technology Lab., Pittsburgh, PA (US); National Energy Technology Lab., Morgantown, WV (US); 1999. https://doi.org/10.2172/810722
6. Yadav S, Mehra A. Experimental study of dissolution of minerals and CO2 sequestration in steel slag. Waste Manag. 2017;64:348-357. https://doi.org/10.1016/j.wasman.2017.03.032
7. Krekel D, Samsun RC, Peters R, Stolten D. The separation of CO2 from ambient air–a techno-economic assessment. Appl Energy. 2018;218:361-381. https://doi.org/10.1016/j.apenergy.2018.02.144
8. Park AH. Carbon dioxide sequestration: chemical and physical activation of aqueous carbonation of Mg-bearing minerals and pH swing process. Doctoral dissertation, The Ohio State University. 2005.
9. Mélières MA, Maréchal C. Climate Change: Past, Present, and Future. 1st ed. John Wiley & Sons; 2015. pp. 298-301.
10. Baldocchi D, Falge E, Gu L, Olson R, Hollinger D, Running S, et al. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull Am Meteorol Soc. 2001;82(11):2415-2434. https://doi.org/10.1175/1520-0477(2001)082%3C2415:FANTTS%3E2.3.CO;2
11. Black TA, Den Hartog G, Neumann HH, Blanken PD, Yang PC, Russell C, et al. Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest. Glob Chang Biol. 1996;2(3):219-229. https://doi.org/10.1111/j.1365-2486.1996.tb00074.x
12. Law BE, Falge E, Gu L, Baldocchi DD, Bakwin P, Berbigier P, et al. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agric For Meteorol. 2002;113(1-4):97-120. https://doi.org/10.1016/S0168-1923(02)00104-1
13. Friedlingstein P, Dufresne JL, Cox PM, Rayner P. How positive is the feedback between climate change and the carbon cycle?. Tellus B: Chem Phys Meteorol. 2003;55(2):692-700. https://doi.org/10.3402/tellusb.v55i2.16765
14. Fung IY, Doney SC, Lindsay K, John J. Evolution of carbon sinks in a changing climate. Proc Natl Acad Sci USA. 2005;102(32):11201-11206. https://doi.org/10.1073/pnas.0504949102
15. Chen B, Chen JM, Liu J, Chan D, Higuchi K, Shashkov A. A vertical diffusion scheme to estimate the atmospheric rectifier effect. J Geophys Res: Atmos. 2004;109(D10). https://doi.org/10.1029/2003JD003925
16. Selin NE. Carbon Footprint, Encyclopedia Britannica. https://www.britannica.com/science/carbon-footprint, (Accessed on 5 March 2024).
17. Peters GP. Carbon footprints and embodied carbon at multiple scales. Curr Opin Environ Sustain. 2010;2(4):245-250. https://doi.org/10.1016/j.cosust.2010.05.004
18. Ozlu E, Arriaga FJ, Bilen S, Gozukara G, Babur E. Carbon Footprint Management by Agricultural Practices. Biology (Basel). 2022;11(10):1453. https://doi.org/10.3390%2Fbiology11101453
19. Gao T, Liu Q, Wang J. A comparative study of carbon footprint and assessment standards. Int J Low-Carbon Technol. 2014;9(3):237-243. https://doi.org/10.1093/ijlct/ctt041
20. Valls-Val K, Bovea MD. Carbon footprint in higher education institutions: a literature review and prospects for future research. Clean Technol Environ Policy. 2021;23(9):2523-2542. https://doi.org/10.1007/s10098-021-02180-2
21. Dechamps P. The IEA world energy outlook 2022-a brief analysis and implications. Eur Energy Clim J. 2023;11(3):100-103. https://doi.org/10.4337/eecj.2023.03.05
22. Manisha Jain. Carbon dioxide emissions from India's industries: data sources and discrepancies, Indira Gandhi Institute of Development Research. https://www.ideasforindia.in/topics/environment/carbon-dioxide-emissions-from-india-s-industries-data-sources-and-discrepancies.html, (Accessed on 5 February 2023).
23. Aguiar A, Chepeliev M, Corong EL, McDougall R, Van Der Mensbrugghe D. The GTAP data base: version 10. J Glob Econ Anal. 2019;4(1):1-27. https://doi.org/10.21642/JGEA.040101AF
24. Paltsev S, Gurgel A, Morris J, Chen H, Dey S, Marwah S. Economic analysis of the hard-to-abate sectors in India. Energy Econ. 2022;112:106149. https://doi.org/10.1016/j.eneco.2022.106149
25. Arora NK, Mishra I. COP26: more challenges than achievements. Environ Sustainability. 2021;4:585-588. https://doi.org/10.1007/s42398-021-00212-7
26. PIB. India's Stand at COP-26. Ministry of environment forest and climate change. 2022. Available at: https://pib.gov.in/PressReleasePage.aspx?PRID=1795071
27. Grafakos S, Trigg K, Landauer M, Chelleri L, Dhakal S. Analytical framework to evaluate the level of integration of climate adaptation and mitigation in cities. Clim Change. 2019;154:87-106. https://doi.org/10.1007/s10584-019-02394-w
28. Sharifi A. Co-benefits and synergies between urban climate change mitigation and adaptation measures: a literature review. Sci Total Environ. 2021;750:141642. https://doi.org/10.1016/j.scitotenv.2020.141642
29. Das LM. Safety aspects of a hydrogen-fuelled engine system development. Int J Hydrog Energy. 1991;16(9):619-624. https://doi.org/10.1016/0360-3199(91)90086-X
30. Damen K, van Troost M, Faaij A, Turkenburg W. A comparison of electricity and hydrogen production systems with CO2 capture and storage. Part A: review and selection of promising conversion and capture technologies. Prog Energy Combust Sci. 2006;32(2):215-246. https://doi.org/10.1016/j.pecs.2005.11.005
31. Bauer N, Edenhofer O, Held H, Kriegler E. Uncertainty of the role of carbon capture and sequestration within climate change mitigation strategies. Greenhouse Gas Control Technologies 7. 2005:931-939. https://doi.org/10.1016/B978-008044704-9/50094-X
32. Wang W, Cao Y. A combined thermodynamic and experimental study on chemical-looping ethanol reforming with carbon dioxide capture for hydrogen generation. Int J Energy Res. 2012;37(1):25-34. https://doi.org/10.1002/er.2976
33. Smith KH, Ashkanani HE, Morsi BI, Siefert NS. Physical solvents and techno-economic analysis for pre-combustion CO2 capture: a review. Int J Greenhouse Gas Control. 2022;118:103694. https://doi.org/10.1016/j.ijggc.2022.103694
34. Rubin ES, Mantripragada H, Marks A, Versteeg P, Kitchin J. The outlook for improved carbon capture technology. Prog Energy Combust Sci. 2012;38(5):630-671. https://doi.org/10.1016/j.pecs.2012.03.003
35. Herzog H. What future for carbon capture and sequestration?. Environ Sci Technol. 2001;35(7):148A-153A. https://doi.org/10.1021/es012307j
36. Rao AB, Rubin ES. A technical, economic, and environmental assessment of amine-based CO2 capture technology for power plant greenhouse gas control. Environ Sci Technol. 2002;36(20):4467-4475. https://doi.org/10.1021/es0158861

37. Adewole JK, Ahmad AL, Ismail S, Leo CP. Current challenges in membrane separation of CO2 from natural gas: a review. Int J Greenhouse Gas Control. 2013;17:46-65. https://doi.org/10.1016/j.ijggc.2013.04.012
38. Zhang Y, Sunarso J, Liu S, Wang R. Current status and development of membranes for CO2/CH4 separation: a review. Int J Greenhouse Gas Control. 2013;12:84-107. https://doi.org/10.1016/j.ijggc.2012.10.009
39. Luis P, Van Gerven T, Van der Bruggen B. Recent developments in membrane-based technologies for CO2 capture. Prog Energy Combust Sci. 2012;38(3):419-448. https://doi.org/10.1016/j.pecs.2012.01.004
40. Brunetti A, Scura F, Barbieri G, Drioli E. Membrane technologies for CO2 separation. J Membr Sci. 2010;359(1-2):115-125. https://doi.org/10.1016/j.memsci.2009.11.040
41. Li L, Zhao N, Wei W, Sun Y. A review of research progress on CO2 capture, storage, and utilization in Chinese academy of sciences. Fuel. 2013;108:112-130. https://doi.org/10.1016/j.fuel.2011.08.022
42. Rochelle G, Chen E, Dugas R, Oyenakan B, Seibert F. Solvent and process enhancements for CO2 absorption/stripping. In: 2005 annual conference on capture and sequestration. Alexandria; 2006.
43. Figueroa JD, Fout T, Plasynski S, McIlvried H, Srivastava RD. Advances in CO2 capture technology-the US department of energy's carbon sequestration program. Int J Greenhouse Gas Control. 2008;2(1):9-20. https://doi.org/10.1016/S1750-5836(07)00094-1
44. Self SJ, Reddy BV, Rosen MA. Review of underground coal gasification technologies and carbon capture. Int J Energy Environ Eng. 2012;3(16):1-8. https://doi.org/10.1186/2251-6832-3-16
45. Veawab A, Aroonwilas A, Tontiwachwuthikul P. CO2 absorption performance of aqueous alkanolamines in packed columns. Am Chem Soc Div Fuel Chem, Preprints. 2002;47(1):49-50.
46. Leung DY, Caramanna G, Maroto-Valer MM. An overview of current status of carbon dioxide capture and storage technologies. Renew Sustain Energy Rev. 2014;39:426-443. https://doi.org/10.1016/j.rser.2014.07.093
47. Li Q, Gupta S, Tang L, Quinn S, Atakan V, Riman RE. A novel strategy for carbon capture and sequestration by rHLPD processing. Front Energy Res. 2016;3:53. https://doi.org/10.3389/fenrg.2015.00053
48. Göttlicher G, Pruschek R. Comparison of CO2 removal systems for fossil-fuelled power plant processes. Energy Convers Manag. 1997;38:S173-S178. https://doi.org/10.1016/S0196-8904(96)00265-8
49. Saran RK, Kumar R, Yadav S. Climate change: mitigation strategy by various CO2 sequestration methods. Int J Adv Res Sci Eng. 2017;6(2):299-308.
50. Olajire AA. A review of mineral carbonation technology in sequestration of CO2. J Pet Sci Eng. 2013;109:364-392. https://doi.org/10.1016/j.petrol.2013.03.013
51. Baciocchi R, Costa G, Lategano E, Marini C, Polettini A, Pomi R, et al. Accelerated carbonation of different size fractions of bottom ash from RDF incineration. Waste Management. 2010;30(7):1310-1317. https://doi.org/10.1016/j.wasman.2009.11.027
52. Huijgen WJ, Witkamp GJ, Comans RN. Mineral CO2 sequestration by steel slag carbonation. Environ Sci Technol. 2005;39(24):9676-9682. https://doi.org/10.1021/es050795f
53. Lackner KS, Butt DP, Wendt CH. Progress on binding CO2 in mineral substrates. Energy Convers Manag. 1997;38:S259-S264. https://doi.org/10.1016/S0196-8904(96)00279-8
54. O'Connor WK, Dahlin DC, Rush GE, Gerdemann SJ, Penner LR, Nilsen DN. Aqueous mineral carbonation. DOE, US. 2005.
55. Sipilä J, Teir S, Zevenhoven R. Carbon dioxide sequestration by mineral carbonation literature review update 2005–2007. Report Vt. 2008;1:2008. Available at: https://web.abo.fi/~rzevenho/MineralCarbonationLiteratureReview05-07.pdf
56. Voormeij DA, Simandl GJ. Ultramafic rocks in British Columbia: delineating targets for mineral sequestration of CO2. Summary of Activities, BC Ministry of Energy and Mines. 2004;23:157-167.
57. Kaliyavaradhan SK, Ling TC. Potential of CO2 sequestration through construction and demolition (C&D) waste—an overview. J CO2 Util. 2017;20:234-242. https://doi.org/10.1016/j.jcou.2017.05.014
58. Teir S, Eloneva S, Fogelholm CJ, Zevenhoven R. Stability of calcium carbonate and magnesium carbonate in rainwater and nitric acid solutions. Energy Convers Manag. 2006;47(18-19):3059-3068. https://doi.org/10.1016/j.enconman.2006.03.021
59. Miao E, Du Y, Zheng X, Zhang X, Xiong Z, Zhao Y, et al. Kinetic analysis on CO2 sequestration from flue gas through direct aqueous mineral carbonation of circulating fluidized bed combustion fly ash. Fuel. 2023;342:127851. https://doi.org/10.1016/j.fuel.2023.127851
60. Bertos MF, Simons SJ, Hills CD, Carey PJ. A review of accelerated carbonation technology in the treatment of cement-based materials and sequestration of CO2. J Hazard Mater. 2004;112(3):193-205. https://doi.org/10.1016/j.jhazmat.2004.04.019
61. Ho HJ, Iizuka A. Mineral carbonation using seawater for CO2 sequestration and utilization: a review. Sep Purif Technol. 2023;307:122855. https://doi.org/10.1016/j.seppur.2022.122855
62. Zevenhoven R, Teir S, Eloneva S. Heat optimisation of a staged gas–solid mineral carbonation process for long-term CO2 storage. Energy. 2008;33(2):362-370. https://doi.org/10.1016/j.energy.2007.11.005
63. Sanna A, Uibu M, Caramanna G, Kuusik R, Maroto-Valer MM. A review of mineral carbonation technologies to sequester CO2. Chem Soc Rev. 2014;43(23):8049-8080. https://doi.org/10.1039/C4CS00035H
64. Björn LO, Govindjee. The evolution of photosynthesis and its environmental impact. In Björn L. (ed) Photobiology. Springer: New York. 2015:207-230. https://doi.org/10.1007/978-1-4939-1468-5_16
65. Formighieri C, Franck F, Bassi R. Regulation of the pigment optical density of an algal cell: filling the gap between photosynthetic productivity in the laboratory and in mass culture. J Biotechnol. 2012;162(1):115-123. https://doi.org/10.1016/j.jbiotec.2012.02.021
66. Melis A. Solar energy conversion efficiencies in photosynthesis: minimizing the chlorophyll antennae to maximize efficiency. Plant Sci. 2009;177(4):272-280. https://doi.org/10.1016/j.plantsci.2009.06.005
67. Tsai DD, Chen PH, Ramaraj R. The potential of carbon dioxide capture and sequestration with algae. Ecol Eng. 2017;98:17-23. https://doi.org/10.1016/j.ecoleng.2016.10.049
68. Sethi D, Butler TO, Shuhaili F, Vaidyanathan S. Diatoms for carbon sequestration and bio-based manufacturing. Biology. 2020;9(8):217. https://doi.org/10.3390/biology9080217
69. Ahmad MA, Aminuddin MA, Razak NF, Cheah WY. Carbon dioxide mitigation by diatoms. Diatoms. 1st ed. Boca Raton:CRC Press; 2024. pp.71-85.

https://doi.org/10.61577/jbs.2024.100003