DESIGN AND SIMULATION OF ELECTROCHEMICAL REGENERATION OF FUEL FROM DIRECT AIR CAPTURE

Thesis submitted towards the partial fulfilment of Master of Engineering degree in Chemical Engineering

By

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I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as part of his "Master of Engineering in Chemical Engineering" studies. All information in this document have been obtained and presented in accordance with academic rules and ethical conduct.

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CERTIFICATION

This is to certify that **Mr. Kundan Deb**, final year student in Master of Chemical Engineering examination in the department of Chemical Engineering, Jadavpur University, bearing Registration No: 163449 has successfully completed the thesis work entitled **"Design And Simulation of Electrochemical Regeneration of Fuel From Direct Air Capture"** under the guidance of **Dr. Raj Kumar Das** during his master degree curriculum. This work has not been reported earlier anywhere and can be approved for submission in partial fulfilment of the requirements for the Master of Engineering in Chemical Engineering.

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CERTIFICATE OF APPROVAL

This thesis is hereby approved as creditable study of an engineering subject carried out and presented in a manner satisfactory to warrant its acceptance as prerequisite to the degree for which it has been submitted. It is understood by this approval that undersigned don't endorse or approve any statement made, opinion expressed or conclusion drawn therein but approve the thesis only for purpose of which it is submitted.

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Thanking you,

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HIGH LIGHTS ;

A review paper on methane formation from algae would likely encompass various aspects of the process, including its mechanisms, environmental implications, potential applications, and challenges. Here are some potential highlights that such a paper might cover:

- **Algal Methanogenesis Mechanisms:** Discuss the biochemical pathways involved in methane formation from algae, focusing on anaerobic digestion or fermentation processes. Highlight the microbial communities responsible for methane production and their interactions with algal biomass.

- **Factors Influencing Methane Production:** Explore the factors that influence methane production from algae, such as algal species, substrate composition, temperature, pH, and reactor design. Discuss how optimizing these factors can enhance methane yield and quality.

- **Environmental Impact:** Assess the environmental implications of algal methanogenesis, including its potential as a renewable energy source and its role in carbon cycling and greenhouse gas emissions. Evaluate the sustainability of algal-based methane production compared to other biofuel options.

- **Applications of Algal Methane:** Explore potential applications of algal-derived methane, including its use as a biofuel for transportation, heat and power generation, and as a feedstock for chemical synthesis. Discuss the economic feasibility and scalability of these applications.

- **Challenges and Future Directions**: Identify current challenges and limitations associated with algal methanogenesis, such as substrate availability, process efficiency, and technological barriers. Propose future research directions aimed at overcoming these challenges and unlocking the full potential of algal-based methane production.

- **Case Studies and Technological Innovations:** Highlight case studies of successful algal methanogenesis projects and innovative technologies developed for efficient methane production from algae. Discuss the lessons learned and opportunities for scaling up these technologies.

- **Policy and Regulatory Considerations:** Discuss policy and regulatory frameworks relevant to algal-based methane production, including incentives, subsidies, and sustainability standards. Analyze the role of government support in fostering the development of this emerging bioenergy sector.

- **Biochemical Characterization of Algal Biomass:** Explore the biochemical composition of different algal species and how it influences their suitability for

methane production. Discuss the role of key macromolecules such as carbohydrates, lipids, and proteins in anaerobic digestion processes.

- **Bioreactor Technologies:** Provide an overview of various bioreactor configurations used for algal cultivation and methane production, including batch, continuous, and hybrid systems. Evaluate the advantages and limitations of each technology in terms of productivity, energy efficiency, and scalability.

- **Co-digestion Strategies:** Investigate the potential synergies of co-digesting algal biomass with other organic waste streams, such as agricultural residues, wastewater sludge, or organic fraction of municipal solid waste. Discuss how co-digestion can improve process stability, methane yield, and resource utilization.

- **Microbial Ecology and Community Dynamics:** Explore the microbial consortia involved in algal methanogenesis and their functional roles in anaerobic digestion ecosystems. Highlight recent advancements in microbial ecology techniques (e.g., metagenomics, metatranscriptomics) for characterizing complex microbial communities.

- **Life Cycle Assessment (LCA):** Conduct a life cycle assessment to quantify the environmental impacts of algal-based methane production, including greenhouse gas emissions, energy consumption, land use, and eutrophication potential. Compare the environmental performance of algal methane with conventional fossil fuels and other renewable energy sources.

- **Techno-economic Analysis (TEA):** Perform a techno-economic analysis to evaluate the economic feasibility and competitiveness of algal-based methane production at different scales. Consider factors such as capital investment, operational costs, revenue streams, and market dynamics.

- **Integration with Other Bio refinery Processes:** Explore opportunities for integrating algal methanogenesis with other bio refinery processes, such as bioethanol production, biodiesel production, or nutrient recovery. Discuss the concept of an integrated bio refinery approach for maximizing resource efficiency and product diversification.

- **Emerging Trends and Innovations:** Highlight emerging trends and innovations in algal biotechnology and methane production, such as genetic engineering of algae for enhanced biomass productivity or metabolic engineering for improved methane yield. Discuss the potential impact of these advancements on the future of algal-based bioenergy.

ABSTRACT

Presently, Direct Air Capture (DAC) stands as a leading contender in the arsenal of strategies to mitigate CO2 emissions, which have reached a critical juncture with the imperative to address 30% of the latest greenhouse gas emissions by 2030. While CO2 removal (CDR) technologies are projected to attain a Technology Readiness Level (TRL) suitable for industrial applications within seven years, the leap to TRL-11, as per the new IEA scale for disruptive technologies, appears improbable due to the intricate process of transitioning from small-scale pilots to industrial implementation, necessitating considerable time and investment. Furthermore, the absence or lack of planning for large-scale validation poses a significant obstacle. This study also pinpoints the critical materials supply chain and the competition posed by the energy transition as additional limiting factors that could impede DAC deployment and diminish its potential contribution during the crucial period when substantial emissions reductions are imperative.

The escalating atmospheric carbon dioxide levels, contributing to global warming, underscore the urgent need for sustainable carbon sequestration methods. In this review, we delve into carbon capture, utilization, and storage using microalgae, emphasizing techniques to enhance carbon dioxide uptake. These include systems integrating wastewater and flue gases, machine learning for strain identification, artificial intelligence, automation, and the circular bio economy. Strategies to boost carbon dioxide uptake by microalgae encompass modified photo bioreactors, membranes, chemical methods, solvents, adapted strains, genetically engineered strains, omics, and nanotechnology. Moreover, we explore the economic feasibility of microalgae-based carbon capture and bioenergy production. On average, micro algal cultivation across 13 million acres has the potential to sequester approximately 0.5 giga tons of CO2, yielding over 300 tons of biomass.

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1. INTRODUCTION

The pressing global challenge of climate change has spurred intensified research into innovative methods for carbon dioxide (CO2) capture and utilization. Among these, algae-based CO2 capture stands out as a promising avenue, offering a sustainable and efficient solution rooted in the natural carbon cycle. Algae, a diverse group of photosynthetic organisms ranging from microalgae to microalgae, possess remarkable capabilities to sequester CO2 from various sources, including industrial flue gases, wastewater, and the atmosphere itself. The inexorable march of civilization has long been intertwined with escalating energy demands, a symbiotic relationship that has propelled humanity into the modern age while inadvertently exacerbating the threat of climate change. Since the advent of the industrial revolution, the voracious appetite for energy has surged unabated, paralleled by a commensurate rise in greenhouse gas emissions, chiefly carbon dioxide (CO2). According to data from the Carbon Dioxide Information Analysis Center, CO2 emissions skyrocketed from a modest 3 metric tons in the mid-18th century to a staggering 8230 tons by the dawn of the 21st century, a trajectory emblematic of the carbon-intensive trajectory of industrialization.

In response to the mounting urgency of climate action, the international community convened in 1997 to forge a seminal agreement aimed at curbing greenhouse gas emissions: the Kyoto Protocol. At its core lay a bold mandate for participating nations to slash their emissions to levels at least 5% below those of 1990 (**Miyamoto, M.; Takeuchi at all, 2019**), underscoring a collective commitment to mitigate the unfolding climate crisis. The Kyoto Protocol, a pioneering endeavor in global climate governance, spurred a flurry of scholarly inquiries into its efficacy and impact, with a burgeoning body of research delving into its multifaceted ramifications. However, as the Kyoto Protocol reached the denouement of its tenure, the imperative for a more inclusive and ambitious climate pact became increasingly apparent. Thus emerged the Paris Agreement, a watershed moment in the annals of climate diplomacy, ushering in a new era of collaborative resolve to confront the existential threat posed by climate change. Conceived in 2015, the Paris Agreement transcends its predecessor by embracing a bottom-up approach, whereby nations autonomously pledge their own nationally determined contributions (NDCs) to mitigate emissions and fortify climate resilience.

Crucially, the Paris Agreement embodies the principles of equity and differentiation, acknowledging the historical responsibility of developed nations for the lion's share of emissions while championing the imperative for global solidarity in charting a sustainable course forward. Moreover, the accord underscores the imperative for mobilizing climate finance and fostering technological innovation to bolster the adaptive capacity of vulnerable nations and expedite the transition to a low-carbon paradigm. As the Paris Agreement continues to galvanize international action and cooperation, its enduring legacy hinges on the collective resolve of nations to translate rhetoric into action, marshaling the requisite political will and financial resources to realize the ambitious objectives enshrined within its hallowed confines. In an epoch defined by existential peril and unprecedented interconnectivity, the Paris Agreement stands as a beacon of hope, a testament to the indomitable spirit of humanity

in the face of adversity, and a harbinger of a more equitable and sustainable future for generations yet unborn.

This review aims to provide a comprehensive overview of the current state-of-the-art in algal CO2 capture technologies, encompassing fundamental principles, technological advancements, and key challenges. By synthesizing findings from interdisciplinary fields spanning biology, biotechnology, engineering, and environmental science, we aim to shed light on the potential of algae as a scalable and eco-friendly tool for mitigating CO2 emissions. The review begins by elucidating the biochemical mechanisms underlying CO2 fixation in algae, highlighting the pivotal role of photosynthesis and carbon concentrating mechanisms (CCMs). Understanding these mechanisms is crucial for optimizing algal cultivation strategies and enhancing CO2 uptake efficiency. Subsequently, we delve into various cultivation systems and reactor designs tailored for algal CO2 capture, ranging from open ponds to closed photo bioreactors, with a focus on their respective advantages and limitations.

Furthermore, this review explores recent innovations in genetic engineering and synthetic biology aimed at enhancing algal CO2 fixation rates and biomass productivity. By manipulating key enzymes involved in carbon assimilation pathways, researchers have unlocked the potential to tailor algal strains for specific CO2 capture applications, paving the way for commercially viable solutions. In addition to technical considerations, we address the environmental and economic sustainability of algal CO2 capture systems, examining factors such as water and nutrient requirements, land use implications, and lifecycle assessments. Furthermore, we discuss the potential synergies between algal CO2 capture and other industrial processes, such as wastewater treatment and biofuel production, which could enhance the overall viability and scalability of the technology.

Despite the promising strides made in algal CO2 capture research, significant challenges remain, including scaling up production to industrial levels, addressing issues of algal contamination and stability, and optimizing downstream processing for CO2 utilization or sequestration. By critically evaluating these challenges and opportunities, this review aims to provide insights for future research directions and the development of sustainable CO2 capture solutions leveraging the power of algae.

The escalating demand for sustainable energy solutions has propelled the exploration of electrochemical processes, notably electrolysis, as pivotal components of the energy conversion landscape. Electrolysis entails the conversion of electrical energy into chemical energy through redox reactions occurring at electrode surfaces. Central to the efficiency and selectivity of electrolysis are the catalysts, which facilitate the electrochemical reactions, thus mitigating energy losses and enhancing reaction kinetics. Traditional catalysts, however, often exhibit limitations such as sluggish kinetics, low selectivity, and susceptibility to corrosion, necessitating the quest for innovative catalyst designs. In this context, nanocatalysts have garnered significant attention owing to their unique physicochemical properties, including high surface area, tunable morphology, and enhanced catalytic activity. This review aims to encapsulate the recent advancements in nanocatalyst synthesis

methodologies tailored for electrolytic applications, highlighting their pivotal role in advancing the frontier of sustainable energy technologies.

Since the pioneering isolation of graphene from graphite by A. Geim and K. Novoselov in 2004 [**K.I. Bolotin a, K.J. Sikes, 2008**], graphene has not only maintained its popularity but has also seen a continuous increase in research interest, as evidenced by the growing number of publications each year. The material scientist community is particularly excited about the potential of graphene as a core material for numerous future applications, owing to its unique mechanical, electrical, optical, and thermal properties. For instance, due to the behavior of charge carriers in graphene, which can be described by the Dirac equation rather than the Schrödinger equation, graphene exhibits remarkable electron mobility of up to 2.5×105 $cm^2V^{-1}s^{-1}$ at room temperature, indicating its potential as a superconductive material for electrodes [**Shuai Ren, Ping Rong, Qi Yu, 2018**].

Moreover, incorporating graphene as an additive for polymer or metal composites has shown potential in producing stronger nanocomposite matrices, thanks to graphene's impressive elastic modulus of 0.5–1.0 TPa and tensile strength of 130 GPa for monolayer defect-free graphene [**R. Al-Gaashani, A. Najjar at all, 2019**]. Additionally, graphene's in-plane thermal conductivity of 3000 $W.mK^{-1}$ makes it an efficient thermal conductor filler for nanofluids, attracting significant interest from experts in the heat transfer field.

The properties of graphene are uniquely dependent on the production method, which can be categorized as either bottom-up or top-down strategies. With bottom-up approaches, such as chemical vapor deposition and epitaxial growth of graphene, a catalyst is employed to promote specific chemical reactions for expanding the carbon-carbon network from a single molecular chain during synthesis. This approach allows for the avoidance of defects in the graphene structure, and the grain size of graphene can be manipulated using the size of the substrate. However, the scalability of this approach is limited due to the dependence of graphene size on substrate selection, and the requirement for expensive equipment poses another challenge, despite this method being considered the most suitable for preparing monolayer graphene.

In the last century, the CO2 level has experienced a slight increase to 408.8 ppm [**Edrisi, S.A.; Tripathi at all, 2022**], with projections anticipating a rise to 600 to 700 ppm, potentially elevating average surface temperatures by 4.5–5 °C [**Dai, Y.; Lai at all, 2022**]. The escalation in CO2 concentration is influenced by a confluence of factors, including unstable financial, technological, and sociological advancements, as well as natural and anthropogenic developments [**Triyanti, A.; Marfai at all, 2021**]. Alongside CO2, other greenhouse gas (GHG) emissions have witnessed significant upticks in recent years, encompassing sulfur hexafluoride (SF6), perfluorocarbons, hydrofluorocarbons (HFC), nitrous oxide (N2O), and methane (CH4) [**Al-Mamoori, A.; Lawson at all,2019, Gimžauskaitė, D.; Aikas at all, 2022**]. According to the International Panel on Climate Change, curtailing GHG emissions by 50–80% is imperative to avert catastrophic environmental degradation [**Rojas-Cuevas, I.-D. at all, 2022**]. Nearly 190 nations convened in Paris in December 2015 (Conference of Parties—COP 21) with the aim of limiting global

temperature increases to 2 °C by the end of the 21st century. COP 21 advocated for various strategies, including enhancing energy efficiency, embracing renewable energy sources, and implementing geoengineering techniques such as afforestation, along with emphasizing the development of carbon capture and storage (CCS) technologies [**Dai, Y.; Lai, F.; Ni, J at all, 2022**]. Hence, CCS is widely recognized as a potentially viable method to curtail global CO2 emissions [**Holz, F.; Scherwath at all, 2021**].

Approximately 60% of CO2 emissions emanate from numerous stationary sources, including industrial facilities, fossil fuel power plants, thermoelectric cement plants, iron and steel mills, gas processing plants, refineries, and power stations, catering to diverse sectors such as industry, transportation, and electricity generation [**Zhao, Y.; Yan, Y.; Lee, at all, 2022**]. Based on the aforementioned analysis, stationary emission sources are anticipated to remain the predominant contributors to greenhouse gas (GHG) emissions resulting from fossil fuel combustion for several decades to come. Electricity generation accounts for 25% of total emissions, while forestry and agriculture contribute 24%. Thermal power plants, typically reliant on coal due to its affordability and accessibility, constitute a major emission source, with emissions averaging around 2249 lbs/MWh [**Zhang, D.; Zou, R.; Wang, X.; Liu, at all, 2021**]. Consequently, there has been a surge of interest in recent times towards novel technologies like CCS, aimed at swiftly extracting CO2 from the atmosphere to combat global warming. **Figure-1** illustrates the primary energy sectors contributing to CO2 emissions the most.

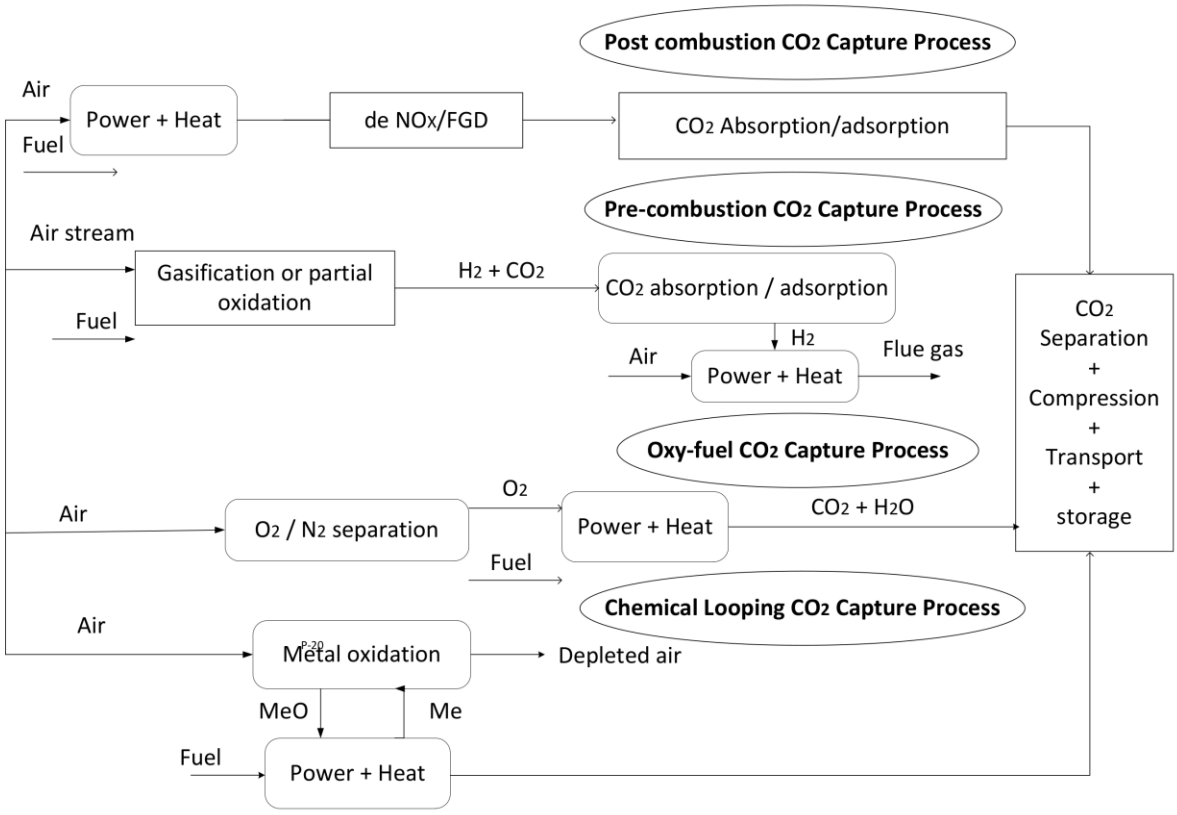


Figure – 1 CO2 capture technologies

The choice of combustion process employed, coupled with the volume of CO2 absorbed, separated, and transported for reuse or storage, serves as the primary determinants of CCS [**Dai, Y.; Lai, F.; Ni, J at all, 2022**]. CCS holds the potential to mitigate CO2 emissions from power plants, thereby aiding in limiting global warming to 2 °C. Post-combustion represents the most mature of the three major CCS technologies, followed by pre-combustion and oxy-fuel combustion. Coal gasification emerges as the optimal option concerning CO2 capture, albeit incompatible with gas-fired power plants. It capitalizes on existing power plant infrastructure, making it feasible as a retrofit technology. Demonstrations have shown the capability to recover 300 t/day of CO2 on a small scale **[Dai, Y.; Lai, F.; Ni, J at all, 2022**].

Oxy-fuel combustion entails the replacement of air with pure oxygen, obviating the need for flue gas de-NOx and enabling the incorporation of 80–98 °C CO2 in the exhaust, rendering it a more efficient and dependable CO2 removal technique. Despite its energy-intensive nature, corrosion is mitigated by the presence of SO2 concentration due to increased energy consumption. Gasification under low O2 pressure in pre-combustion CCS yields syngas (CO + H2) through fuel pretreatment [**Dai, Y.; Lai, F.; Ni, J at all, 2022**]. High CO2 concentrations in the fuel gas streamline separation compared to other methods, fostering the production of H2 as an energy transport medium, thereby offsetting some operational costs of the technology.

The objective of this paper is to offer a comprehensive overview of the status of carbon capture systems, encompassing both conventional and emerging approaches, and present CO2 as a potential feedstock for methane (CH4) production. Furthermore, it emphasizes refining the concept and fostering research on CO2 capture and utilization to mitigate storage challenges associated with current CCS technology, thus prioritizing sustainability for future generations.

2. METHODOLOGY:

The methodology of this literature review was to scrutinize the advantages and limitations of contemporary carbon capture systems and porous carbon-based adsorbents for CO2 adsorption. Furthermore, it aimed to delve into the hurdles and possibilities concerning CO2 conversion into methane. The methodology section delineates the process of literature exploration, gathering, and organization by pinpointing existing knowledge gaps. A thorough analysis of articles and literature sourced from peer-reviewed journals was conducted utilizing various scientific databases and search engines, including NCBI, Google Scholar, Scopus, Science Direct, Web of Science, and major publishers. The quest for pertinent literature was restricted to studies spanning from 2000 to 2023 to maintain relevance and currency in drafting this manuscript. The literature exploration for this manuscript predominantly concentrated on research conducted between 2000 and 2023. To encapsulate the essence of the paper's main theme, several key terms were employed during the literature search, encompassing zeolite, activated carbon, graphene, silica, metal–organic framework, as well as CO2 capture and conversion. Articles containing the most germane content were

chosen subsequent to a thorough evaluation and review of their abstracts. To mitigate translation challenges, articles published in languages other than English were excluded.

3. OBJECTIVE

The objective of focusing on the electrochemical regeneration of fuel from direct air capture (DAC) is to explore a sustainable and innovative approach to address climate change and energy transition challenges. Here are specific objectives for such a study:

- **Technological Review:** Provide a comprehensive overview of electrochemical methods for regenerating fuel from captured CO2, highlighting the principles, mechanisms, and current state-of-the-art technologies in this field.

- Efficiency Assessment: Evaluate the efficiency and energy requirements of electrochemical processes used in fuel regeneration from DAC, comparing them to traditional fuel production methods and other CO2 utilization pathways.

- Environmental Impact Analysis: Assess the environmental benefits and potential drawbacks of electrochemical DAC-based fuel regeneration, including greenhouse gas emissions reduction, air pollution mitigation, and resource utilization.

- **Economic Viability:** Analyze the economic feasibility and competitiveness of electrochemical DAC-based fuel regeneration compared to conventional fuel production methods, considering factors such as capital and operating costs, market demand, and policy incentives.

- **Technological Challenges and Solutions:** Identify key technical challenges and barriers hindering the widespread adoption of electrochemical DAC-based fuel regeneration, and propose potential solutions and innovations to overcome these challenges.

- **Integration Opportunities:** Explore opportunities for integrating electrochemical DAC-based fuel regeneration with renewable energy sources, grid balancing technologies, and carbon capture and storage (CCS) systems to create synergies and enhance overall system efficiency.

- **Policy and Regulatory Considerations:** Examine existing policies, regulations, and incentives related to electrochemical DAC-based fuel regeneration, and propose policy recommendations to support its development, deployment, and commercialization.

- **Market Analysis and Potential:** Investigate the market potential, growth prospects, and investment opportunities for electrochemical DAC-based fuel regeneration technologies in various sectors, including transportation, industry, and energy storage.

- **Case Studies and Demonstrations:** Highlight case studies, pilot projects, and demonstrations showcasing the application and scalability of electrochemical DAC-based fuel regeneration technologies in real-world settings.

- **Future Outlook:** Provide insights into future trends, research directions, and potential breakthroughs in electrochemical DAC-based fuel regeneration, and discuss its role in achieving global climate goals and transitioning to a sustainable energy future.

4. THE IMPACT OF GREENHOUSE GASES ON THE ENVIRONMENTAL SITUATION IN THE WORLD

The relentless march of climate change is propelled by the relentless surge in emissions of carbon dioxide, the primary culprit among greenhouse gases. Stemming predominantly from fossil fuel combustion (including oil, coal, peat, and gas) and agricultural activities (such as animal husbandry), carbon dioxide emissions have surged by a staggering 40% since the pre-industrial era, exacerbating the inexorable rise in global temperatures. Moreover, atmospheric concentrations of other potent greenhouse gases, including nitrous oxide (N2O) and methane (CH4), have ballooned by 20% and 150%, respectively, since 1750, amplifying the climatic perturbations wrought by humanity's voracious energy appetite [**Xu, G.; Li at all, 2021**].

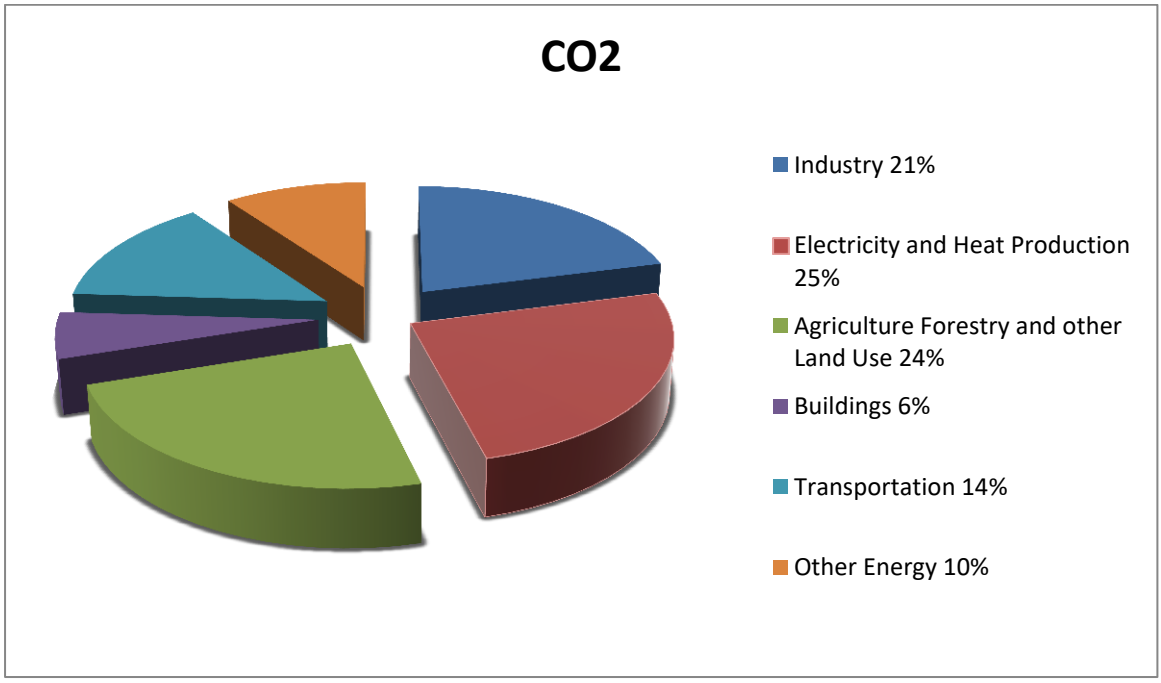
The insidious specter of global warming, compounded by escalating greenhouse gas emissions, exacts a mounting toll on the world's ecological integrity and socioeconomic fabric. Against this backdrop, the imperative for concerted action to mitigate emissions and fortify climate resilience has never been more acute. Notably, the landmark Paris Agreement of 2015, underpinned by the Intended Nationally Determined Contributions (INDC) framework, enshrines a collective commitment to limit the global temperature rise to below 2 degrees Celsius in the 21st century, marking a pivotal juncture in global climate governance. Yet, despite nascent signs of progress, the specter of climate change continues to loom large, precipitating a litany of dire consequences for ecosystems, economies, and human well-being. From intensifying extreme weather events to exacerbating food insecurity and biodiversity loss, the pernicious impacts of climate change reverberate far and wide, transcending geographical boundaries and socioeconomic strata [**Paiva, S.L.; Savi, at all, 2014**].

An incipient shift towards dicarbonization is discernible on the global stage, epitomized by a modest downtrend in carbon dioxide emissions among major economies. Notably, the share of China's carbon dioxide emissions, the world's largest emitter, witnessed a marginal decrease from 29.3% in 2016 to 28.8% in 2019, reflecting nascent strides towards carbon neutrality [**Pan, S.Y.; Chiang, at all,2018**].

However, the efficacy of conventional emissions reduction measures alone remains insufficient to arrest the ominous trajectory of climate change. Against this backdrop, the imperative for ramping up research and innovation in carbon capture and storage (CCS) technologies assumes paramount significance. Despite the burgeoning corpus of scholarly literature on CCS, significant knowledge gaps persist, underscoring the urgent need for concerted research and development efforts to unlock the full potential of this nascent technology.

5. METHODS OF CO2 CAPTURE

As discussed before, post-combustion is the most close-to-market CCS strategy (Vega et al., 2018) as shown in Fig. 1. Although many post-combustion CO2 capture technologies such as absorption, adsorption, and membrane have been explored, none of them provides an ideal solution due to the significant amount of flue gas emitted from power plants and mass transfer limitations in these methods (Yu et al., 2012). In addition, the storage of carbon dioxide in depleted oil and gas reservoirs, mined



Global Greenhouse Gas Emissions Data **(IPCC 2014)**

Carbon dioxide (CO2) capture methods are techniques used to capture carbon dioxide emissions from various sources such as power plants, industrial processes, and transportation. These methods are crucial for mitigating climate change by reducing the amount of CO2 released into the atmosphere. Here are some common CO2 capture methods:

1) **Pre-combustion capture:** This method involves capturing CO2 before the fuel is burned. In processes like gasification, carbonaceous fuels such as coal or biomass are converted into a synthesis gas (syngas) composed mainly of hydrogen and carbon

monoxide. The CO2 is then separated from the syngas before combustion, leaving a hydrogen-rich gas that can be used as fuel.

$$CO + H_2O \leftrightarrow H_2 + CO_2 \qquad \Delta H = -41KJ/mol$$

1.1. **Gasification:** Pre-combustion capture typically starts with a process called gasification, where the solid or liquid fuel is converted into a synthesis gas (syngas) consisting mainly of hydrogen (H2) and carbon monoxide (CO). Gasification involves reacting the fuel with a controlled amount of oxygen (O2) or steam (H2O) at high temperatures and pressures in the presence of a gasification agent, such as air, oxygen, or steam.

1.2. **Carbon Capture:** After gasification, the syngas undergoes a CO2 capture step to separate the CO2 from the hydrogen and carbon monoxide. This separation process can be achieved using various techniques, including:

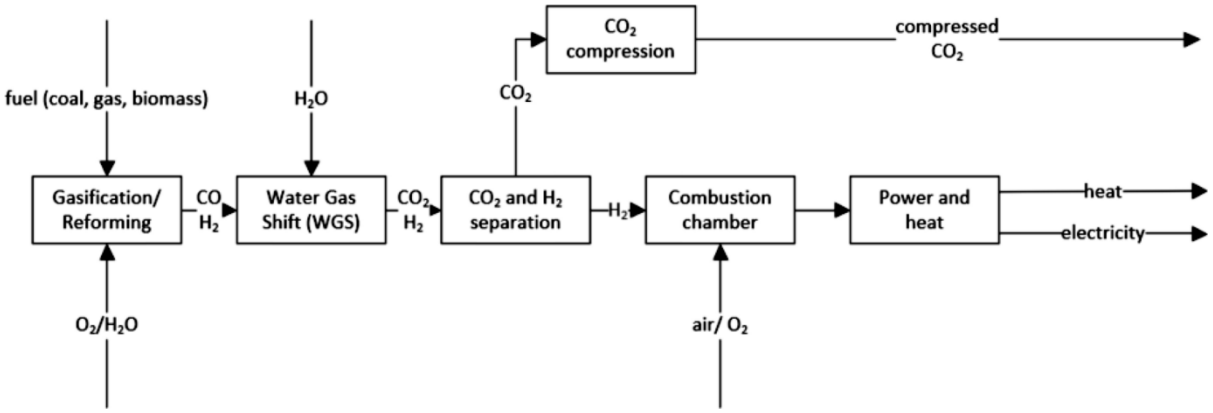
1.3. **Water-Gas Shift (WGS) Reaction**: The water-gas shift reaction converts carbon monoxide (CO) and water vapor (H2O) into CO2 and hydrogen (H2) over a catalyst. By adjusting the conditions, such as temperature and pressure, the equilibrium of the reaction can be shifted to favor the production of CO2.

1.4. **Pressure Swing Adsorption (PSA):** Pressure swing adsorption involves passing the syngas through a bed of adsorbent material that selectively adsorbs CO2 while allowing hydrogen and carbon monoxide to pass through. The CO2 is then desorbed from the adsorbent material under reduced pressure, producing a high-purity CO2 stream.

1.5. **Physical Solvent Absorption**: Physical solvents, such as Selexol or Rectisol, can be used to selectively absorb CO2 from the syngas based on differences in solubility. The CO2-rich solvent is then regenerated under different conditions, releasing the captured CO2 for storage or utilization.

1.6. **Hydrogen Production:** Once the CO2 is captured, the remaining hydrogen-rich syngas can be used for various applications, such as hydrogen production for fuel cells, ammonia synthesis, or as a feedstock for chemical processes.

1.7. **CO2 Compression and Storage:** After capture, the CO2 must be compressed to a high pressure for transportation and storage. Captured CO2 can be stored underground in geological formations, such as depleted oil and gas reservoirs, deep saline aquifers, or carbonate formations, through a process known as carbon capture and storage (CCS).



Pre-combustion. (Madejski et al. 2022)

- **Benefits:**
  - **High-Purity CO2 Stream:** Pre-combustion capture produces a flue gas stream with a high concentration of CO2, simplifying the CO2 capture process and reducing energy requirements.
  - **Hydrogen Production**: Pre-combustion capture can produce high-purity hydrogen as a valuable by product for various industrial applications.
  - **Efficiency:** By capturing CO2 before combustion, pre-combustion capture can potentially achieve higher capture efficiencies compared to post-combustion capture methods
- **Challenges:**
  - **Complexity:** Pre-combustion capture systems can be more complex and require additional equipment compared to post-combustion capture, increasing capital and operating costs.
  - **Integration:** Retrofitting existing power plants or industrial facilities with pre-combustion capture systems may require significant modifications and integration with gasification units, hydrogen production units, and CO2 capture equipment.
  - **Cost:** The cost of implementing pre-combustion capture systems, including gasification units, CO2 capture equipment, and CO2 compression and storage facilities, can be substantial.

2. **Post-combustion capture**: Post-combustion capture involves removing CO2 from the flue gas emitted by combustion processes. This method is applicable to existing power plants and industrial facilities. Techniques such as chemical absorption, physical adsorption, and membrane separation are commonly used to capture CO2 from flue gases. An equation representing the reversible absorption–regeneration reaction is shown below.

$$C_2H_4OHNH_2 + H_2O + CO \leftrightarrow C_2H_4OHNH_3^+ + HCO_3^-$$

2.1. **Flue Gas Composition**: In combustion processes, fuel is burned in the presence of air, resulting in the generation of flue gas containing various gases, including CO2, nitrogen (N2), water vapor (H2O), oxygen (O2), and trace pollutants such as sulfur dioxide (SO2) and nitrogen oxides (NOx). The flue gas typically exits the combustion chamber at elevated temperatures and pressures.

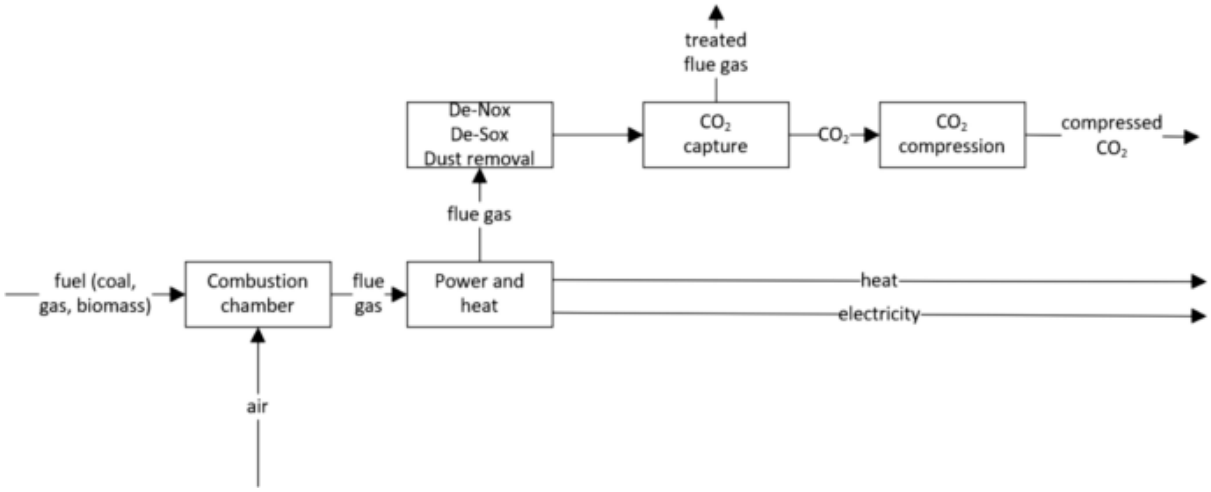
2.2. **CO2 Capture:** Post-combustion capture involves separating CO2 from the flue gas after combustion has occurred. This separation process can be achieved using various chemical, physical, or biological techniques, including:

2.3. **Chemical Absorption**: In chemical absorption, a liquid solvent, such as aqueous amines, is used to selectively absorb CO2 from the flue gas. The CO2-rich solvent is then separated from the flue gas and processed to release the captured CO2 for storage or utilization. The solvent can be regenerated and reused in a continuous cycle.

2.4. **Physical Adsorption:** Physical adsorption involves using solid materials, known as adsorbents, to capture CO2 from the flue gas through physical adsorption processes such as adsorption onto porous surfaces or molecular sieving. Once saturated with CO2, the adsorbent is regenerated by reducing pressure or increasing temperature, releasing the captured CO2 for storage or utilization.

2.5. **Membrane Separation:** Membrane separation utilizes semi-permeable membranes to selectively separate CO2 from the flue gas based on differences in molecular size, solubility, or diffusion rates. The CO2-enriched permeate stream can then be compressed and purified for storage or utilization, while the remaining flue gas is discharged.

2.6. **CO2 Compression and Storage:** Once captured, the CO2 must be compressed to a high pressure for transportation and storage. Captured CO2 can be stored underground in geological formations, such as depleted oil and gas reservoirs, deep saline aquifers, or carbonate formations, through a process known as carbon capture and storage (CCS).



Post-combustion. (Madejski et al. 2022)

- **Benefits**:
  - **Applicability to Existing Infrastructure:** Post-combustion capture can be retrofitted to existing power plants and industrial facilities without major modifications, making it a versatile option for reducing CO2 emissions.
  - **Flexibility:** PCC can be applied to a wide range of combustion processes and fuels, including coal, natural gas, biomass, and municipal solid waste.
  - **Potential for Carbon Neutrality:** When combined with carbon capture and storage (CCS), PCC can enable the production of low-carbon or carbon-neutral energy from fossil fuels.
- **Challenges**:
  - **Energy Intensity:** Post-combustion capture processes can be energy-intensive, requiring significant amounts of energy for CO2 separation, compression, and storage, which may increase operating costs and reduce overall efficiency.
  - **Cost:** The cost of implementing PCC systems, including capital costs for equipment, operating costs for chemicals and utilities, and expenses associated with CO2 transportation and storage, can be significant.
  - **Space and Infrastructure Requirements:** PCC systems may require additional space and infrastructure for CO2 capture equipment, solvent regeneration units, and CO2 compression and storage facilities, particularly for large-scale applications.

3. **Oxy-fuel combustion**: In oxy-fuel combustion, the fuel is burned in a mixture of pure oxygen and recycled flue gas instead of air. This results in a flue gas stream consisting mainly of CO2 and water vapor, which can be easily separated. The captured CO2 can then be compressed and stored or utilized in various industrial processes.

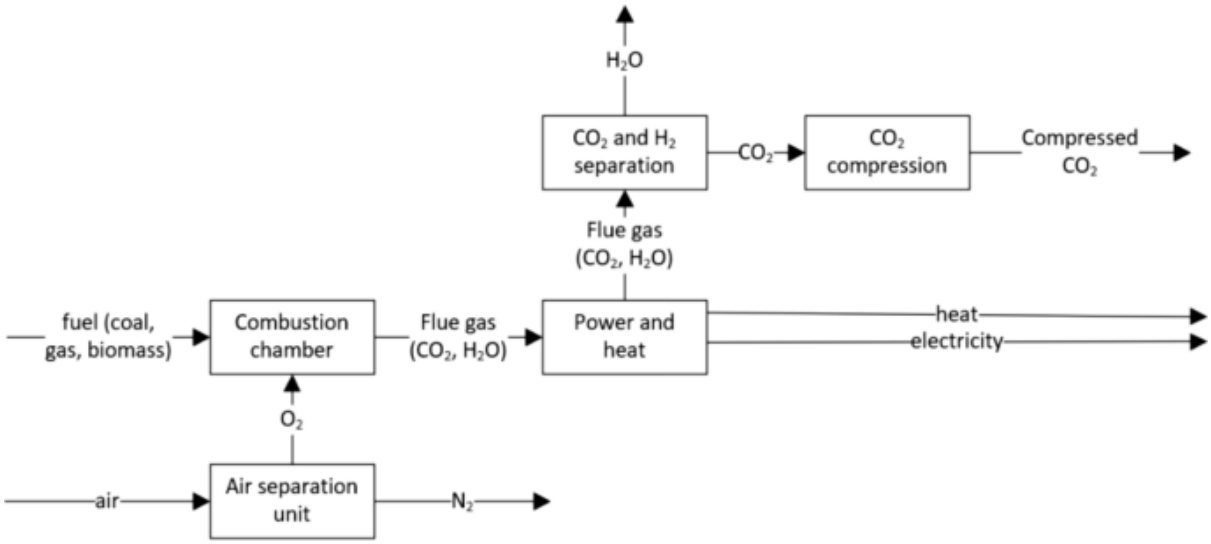
3.1. **Principle:** In traditional combustion processes, air is used as the oxidant, consisting mainly of nitrogen (N2) and oxygen (O2). However, when fuels are burned in air, the flue gas contains a high concentration of nitrogen, which makes capturing CO2 from the flue gas more challenging and energy-intensive. In oxy-fuel combustion, the nitrogen in the air is replaced with pure oxygen, resulting in a flue gas stream consisting primarily of CO2 and water vapor.

3.2. **Oxygen Separation:** To obtain pure oxygen for oxy-fuel combustion, air must undergo a separation process to remove nitrogen. This can be achieved using various methods such as cryogenic distillation, pressure swing adsorption, or membrane separation. Once separated, the pure oxygen is mixed with recycled flue gas, which contains CO2 and water vapor from previous combustion cycles.

3.3. **Fuel Combustion**: The fuel, typically coal, natural gas, or biomass, is burned in the oxygen-enriched atmosphere created by mixing pure oxygen with recycled flue gas. The absence of nitrogen in the combustion environment results in higher flame temperatures and faster combustion rates compared to air-fuel combustion.

3.4. **CO2 Capture:** During combustion, the CO2 generated from burning the fuel is concentrated in the flue gas, along with water vapor. Since the flue gas consists primarily of CO2 and water vapor, capturing CO2 from oxy-fuel combustion is more straightforward and energy-efficient compared to traditional air-fuel combustion processes. CO2 capture can be achieved through techniques such as chemical absorption, physical adsorption, or membrane separation.

3.5. **CO2 Compression and Storage**: Once captured, the CO2 is separated from the flue gas and compressed to a high pressure for transportation and storage. Captured CO2 can be stored underground in geological formations, such as depleted oil and gas reservoirs or deep saline aquifers, through a process known as carbon capture and storage (CCS).



Oxy-combustion. (Madejski et al. 2022)

- **Benefits**:
  - **High-Purity CO2 Stream:** Oxy-fuel combustion produces a flue gas stream with a high concentration of CO2, simplifying the CO2 capture process and reducing energy requirements.
  - **Reduced Emissions:** By eliminating nitrogen from the combustion process, oxy-fuel combustion reduces emissions of nitrogen oxides (NOx), particulate matter, and other pollutants.
  - **Compatibility with CCS:** The high-purity CO2 stream generated by oxy-fuel combustion is well-suited for carbon capture and storage (CCS), enabling significant reductions in CO2 emissions from power plants and industrial facilities.
- **Challenges**:

- **Oxygen Separation**: The process of separating oxygen from air can be energy-intensive and costly, impacting the overall efficiency and economics of oxy-fuel combustion.
- **Corrosion and Materials** Compatibility: Oxy-fuel combustion environments can be more corrosive than traditional air-fuel combustion, requiring special materials and engineering considerations to ensure equipment reliability and longevity.
- **Scale-up and Commercialization**: While oxy-fuel combustion has been demonstrated at pilot and demonstration scales, widespread commercial deployment requires overcoming technical, economic, and regulatory challenges.

4. **Chemical looping combustion:** This is a combustion process where a metal oxide, such as iron oxide or copper oxide, acts as an oxygen carrier. The metal oxide reacts with the fuel to produce heat, water, and a metal oxide reduced in oxygen content. The reduced metal oxide is then oxidized by air, regenerating the metal oxide and producing a stream of CO2 that can be captured.

4.1. **Principle:** CLC operates on the principle of using metal oxides as oxygen carriers to facilitate combustion while separating CO2 from the flue gas without the need for additional separation steps.

4.2. **Oxygen Carrier**: In CLC, a solid metal oxide, such as iron oxide (Fe2O3) or copper oxide (CuO), serves as the oxygen carrier. These metal oxides have the ability to release oxygen when heated and to capture oxygen when cooled.

4.3. **Fuel Combustion**: CLC involves two interconnected fluidized bed reactors: a fuel reactor and an air reactor. In the fuel reactor, the metal oxide acts as the oxygen carrier and reacts with the fuel (example- coal, natural gas) to combust it. The metal oxide is reduced, releasing oxygen and forming metal particles (example- iron or copper) and CO2.

4.4. **Oxygen Transfer:** The metal particles carrying oxygen are then transferred to the air reactor, where they react with air to regenerate the metal oxide. This reaction releases heat, which can be used for power generation or other industrial processes. Meanwhile, the CO2 produced in the fuel reactor is captured without the need for additional separation steps.

4.5. **Closed Loop**: CLC operates in a closed-loop system, where the metal oxide circulates between the two reactors, continuously transferring oxygen back and forth. This eliminates the need for separate processes to capture CO2 from the flue gas, simplifying the overall carbon capture process.

Benefits:

- **Efficient Carbon Capture**: CLC enables efficient capture of CO2 from combustion processes while minimizing energy penalties associated with traditional carbon capture technologies.

- **Lower Cost:** Compared to post-combustion capture methods, CLC can potentially reduce costs by eliminating the need for additional separation equipment.
- **Compatibility with Existing Infrastructure**: CLC can be retrofitted to existing power plants or industrial facilities, leveraging existing infrastructure and reducing implementation costs.

Challenges:

- **Oxygen Carrier Performance:** The performance and stability of the metal oxide oxygen carriers are crucial for the efficiency and reliability of CLC systems. Research is ongoing to develop durable and cost-effective oxygen carriers.
- **Scale-up and Commercialization:** While CLC has shown promise at the laboratory scale, scaling up the technology for commercial applications requires addressing engineering challenges and demonstrating long-term reliability.
- **Integration with Power Generation:** Integration of CLC systems with power generation processes requires careful design and optimization to ensure efficient operation and compatibility with existing power plant configurations.

5. **Biological capture:** Certain microorganisms, such as certain types of algae and bacteria, can capture CO2 through photosynthesis or other biological processes. These organisms can be cultivated in bioreactors or ponds and used to capture CO2 from industrial flue gases or directly from the atmosphere.

5.1. **Photosynthesis:** The primary mechanism of biological capture is photosynthesis, a natural process by which green plants, algae, and some bacteria convert CO2 from the atmosphere into organic carbon compounds, such as carbohydrates, using sunlight as energy. During photosynthesis, plants absorb CO2 through tiny pores called stomata in their leaves and incorporate carbon atoms into their tissues.

5.2. **Carbon Fixation:** Once absorbed, the carbon dioxide is chemically converted into organic molecules through a series of enzymatic reactions. The carbon is "fixed" into organic compounds, which are used by the organism for growth, reproduction, and energy storage.

5.3. **Carbon Storage**: As plants and other photosynthetic organisms grow, they accumulate organic carbon in their biomass. This stored carbon remains sequestered in the tissues of living organisms or in organic matter such as roots, stems, leaves, and soil. Some organisms, such as trees, can store carbon for long periods, potentially for decades or even centuries.

5.4. **Bioenergy with Carbon Capture and Storage (BECCS)**: In addition to natural biological capture, there are also engineered approaches that utilize biological organisms for carbon capture. Bioenergy with Carbon Capture and Storage (BECCS) is one such approach that involves growing biomass, such as energy crops or algae, and using it as a feedstock for bioenergy production, such as biofuels or biogas. The CO2 emitted during bioenergy combustion is captured and stored underground, effectively removing CO2 from the atmosphere.

5.5. **Algae-based Systems**: Algae are particularly efficient at capturing CO2 due to their rapid growth rates and high surface area-to-volume ratio. Algae can be cultivated in ponds, bioreactors, or even photo bioreactors using wastewater or CO2-rich flue gases from industrial sources. Algae convert CO2 into biomass through photosynthesis, and the harvested algae biomass can be used for biofuels, animal feed, or other applications.

- **Benefits:**
  - **Natural and Renewable:** Biological capture utilizes natural biological processes and does not require energy-intensive chemical reactions or equipment.
  - **Carbon Sequestration:** Plants and other photosynthetic organisms act as natural carbon sinks, sequestering CO2 from the atmosphere and storing it in biomass and soil.
  - **Versatility:** Biological capture can be implemented in various forms, from reforestation and afforestation projects to the cultivation of algae for biofuel production.
- **Challenges:**
  - **Limited Capacity:** The capacity of biological capture to remove CO2 from the atmosphere is limited by factors such as land availability, climate conditions, and growth rates of organisms.
  - **Carbon Cycling:** While biological capture can temporarily store carbon in biomass and soil, the carbon may be released back into the atmosphere through decomposition or land use changes.
  - **Competition for Resources:** Large-scale implementation of biological capture may compete with other land uses, such as agriculture or urban development, and may require careful management to avoid negative environmental impacts.

6. **Direct air capture (DAC):** DAC involves capturing CO2 directly from the atmosphere using chemical processes or materials such as solid sorbents or liquid solvents. This method has the potential to remove CO2 from the atmosphere at large scales but is currently more expensive compared to capture from concentrated sources like power plants.

6.1. **Capture Process:** DAC systems typically use chemical processes or materials to selectively capture CO2 molecules from the air. These capture materials, known as sorbents or adsorbents, have a high affinity for CO2, allowing them to efficiently trap CO2 molecules while allowing other gases in the air, such as nitrogen and oxygen, to pass through.

6.2. **Adsorption or Absorption:** There are two primary mechanisms used in DAC systems for capturing CO2:

6.2.1. **Adsorption:** Adsorption involves physically or chemically binding CO2 molecules to the surface of a solid material. Porous materials, such as activated

carbon or metal-organic frameworks (MOFs), are commonly used as adsorbents in DAC systems. CO2 molecules adhere to the surface of these materials through weak chemical interactions, effectively removing them from the air.

Chemical absorption, or chemisorption, is commonly used in post-combustion capture. In the process, a chemical reaction of the component to be absorbed occurs in the liquid. The chemical absorption methods are the most frequently used CO2 separation methods. The main advantage of chemical absorption is the high purity of the carbon dioxide product stream (more than 99% CO2). Thus, no further purification step is necessary. However, a high energy requirement is needed for the downstream detergent regeneration step.

Amines

Amine scrubbing is a method for CO2 separation. Monoethanolamine (MEA) and methyldiethanolamine (MDEA) can be used for this procedure. In this process, the gas to be purified flows into a container at elevated pressure. Finely distributed droplets of the amine absorber are sprayed into it. The carbon dioxide first dissolves in water and is then bound to mono ethanolamine in a chemical reaction. The remaining gas is thus purified of CO2.

$R\text{-}NH_2 + CO_2 = R\text{-}NHCOO^- + H^+$

Amino acid salts

Amino acid salts offer an alternative to amines for CO2 separation. These salts are formed by neutralizing amino acids with potent bases like sodium or potassium hydroxide, or they can be directly used as salts. In a study by(**Liu et al,2012**), N-substituted amino acid salts were employed for CO2 separation. These salts were dissolved in polyethylene glycol, where they could reversibly absorb carbon dioxide in a 1:1 ratio. The absorbed CO2 was then converted into oxazolidinones, eliminating the need for CO2 desorption. One advantage of using amino acids is their stability against oxidative and thermal degradation, coupled with low toxicity. **(Madejski et al. 2022)**

Carbonates

Carbonates represent another possibility for chemical absorption. Absorption of carbon dioxide in aqueous solutions

$$\begin{array}{ccccc} CO_2\,(g) & & H_2O\,(g) & & \\ \uparrow\downarrow & & \uparrow\downarrow & & \\ CO_2\,(aq) & + H_2O & \rightleftharpoons & H_2CO_3 & \\ & \uparrow\downarrow & & \uparrow\downarrow & \end{array}$$

$$CO_2(aq) + OH^- \rightleftharpoons HCO_3^-$$
$$\downarrow\uparrow$$
$$CO_3^-$$

The equilibrium reactions depicted above illustrate the absorption of carbon dioxide in aqueous solutions. However, it's important to note that the rate of carbon dioxide absorption is constrained by the rate of hydrogen carbonate formation. This means that the speed at which carbon dioxide is absorbed depends on how quickly hydrogen carbonate is produced in the solution. **(Fischedick et al. 2015)**

6.2.2. **Absorption:** Absorption involves dissolving CO2 molecules in a liquid solvent. Liquid solvents with high CO2 affinity, such as aqueous amines or ammonia-based solutions, are used to absorb CO2 from the air. Once absorbed, the CO2-rich solvent is separated from the air and processed to release the captured CO2.

Chemical adsorption involves the formation of chemical bonds, like ionogenic or covalent bonds, between the adsorbed substance and the surface of a solid material.

Amine-based

Amine-based adsorbents utilize amines to functionalize solid porous materials. It's preferred to have a high density of amine groups on the carrier material. Solid adsorbents are often functionalized with polymeric amines, including polyaniline, polyethyleneimine, polyallylamine, polypropyleneimine, aminodendrimers, or hyper branched polyamines. **(Varghese and Karanikolos 2020)**

Metal oxides

Metal oxides, such as activated aluminum oxide modified with sodium hydroxide, can also be employed for CO2 adsorption. Research has investigated their use in fixed bed column adsorption systems under various conditions like different temperatures, time periods, and sodium hydroxide concentrations. **(Auta et al. 2013).**

Additionally, CO2 capture can be achieved using mesoporous alumina produced via a sol–gel process. This alumina possesses a large surface area and pore volumes, with closely distributed pores. It offers both chemical and physical adsorption sites for CO2 on its surface.

6.3. **Regeneration:** After capturing CO2, the sorbents or solvents must be regenerated to release the captured CO2 for storage or utilization. This typically involves applying heat to the sorbents to desorb the CO2 molecules or changing the conditions to release CO2 from the solvent.

6.4. **Storage or Utilization:** The captured CO2 can be stored underground in geological formations, used in industrial processes, or converted into valuable products such as synthetic fuels, chemicals, or construction materials through carbon utilization technologies.

- **Benefits:**
  - **Versatility:** DAC can capture CO2 from any source, making it a versatile technology for reducing atmospheric CO2 levels.
  - **Decentralization:** DAC systems can be deployed anywhere, independent of the location of CO2 emissions sources.
  - **Carbon Removal:** DAC has the potential to remove CO2 directly from the atmosphere, helping to mitigate climate change and address carbon neutrality goals.
- **Challenges:**
  - **Energy Intensity:** DAC systems require significant energy input, primarily for capturing CO2 and regenerating the capture materials, which can increase costs and carbon emissions if the energy comes from fossil fuels.
  - **Cost:** Current DAC technologies are relatively expensive compared to other carbon capture methods, primarily due to energy requirements and material costs.
  - **Scale:** Scaling up DAC to capture significant amounts of CO2 from the atmosphere remains a challenge, requiring substantial infrastructure and investment.

7. **Enhanced weathering:** This method involves accelerating natural weathering processes, which naturally absorb CO2 over geological timescales. Materials such as crushed silicate rocks are spread over large areas, where they react with CO2 in the atmosphere to form stable carbonates. Enhanced weathering is a method for capturing carbon dioxide (CO2) from the atmosphere by accelerating natural geological processes that remove CO2 over long timescales. Here's an explanation:

7.1. **Process:** Enhanced weathering involves spreading certain minerals, typically silicate rocks such as olivine or basalt, over large land areas or in coastal waters. When these minerals react with carbon dioxide in the atmosphere, they undergo a series of chemical reactions that result in the formation of stable carbonate minerals.

7.2. **Chemical Reaction**: The primary reaction involved in enhanced weathering is the reaction between carbon dioxide (CO2) and the minerals, which typically involves the following steps:

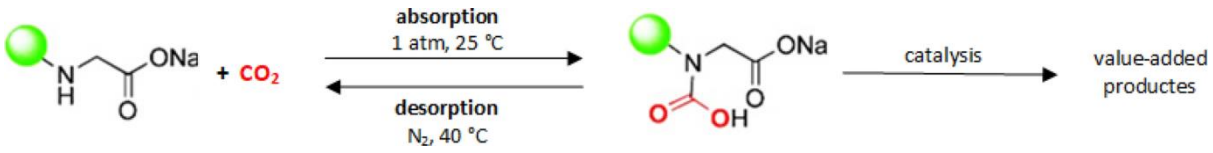
7.3. **Carbonation**: CO2 from the atmosphere dissolves in water to form carbonic acid (H2CO3). This weak acid reacts with minerals such as olivine (Mg2SiO4) or basalt (CaSiO3) to form bicarbonate ions (HCO3-) and dissolved cations like magnesium (Mg2+), calcium (Ca2+), or iron (Fe2+).

7.4. **Mineral Dissolution**: The minerals dissolve as a result of the carbonation process, releasing these dissolved ions into solution.

7.5. **Carbonate Formation**: The bicarbonate ions combine with calcium, magnesium, or iron ions in solution to form carbonate minerals such as calcite (CaCO3), magnesite (MgCO3), or siderite (FeCO3).

7.6. **Carbon Sequestration**: The newly formed carbonate minerals are stable and can persist for thousands to millions of years, effectively removing CO2 from the atmosphere over geological timescales.

- **Benefits:**
  - **Carbon Removal**: Enhanced weathering can potentially remove significant amounts of CO2 from the atmosphere, helping to mitigate climate change.
  - **Natural Processes**: It leverages natural geological processes, requiring minimal technological intervention once the minerals are spread.
  - **Mineral Resources:** Utilizes abundant minerals such as olivine and basalt, which are widely available.
- **Challenges:**
  - **Scale and Speed**: The process may take decades to millennia to sequester significant amounts of CO2, limiting its ability to rapidly mitigate climate change.
  - **Cost:** The cost of mining, transporting, and spreading minerals over large areas may be prohibitive.
  - **Environmental Impact:** Large-scale mining and mineral spreading operations could have environmental impacts, such as habitat disruption and energy consumption.



Reaction of the N-substituted amino acid with carbon dioxide. (**Liu et al. 2012**)

6. CO2 CAPTURE USING ALGAE CULTIVATION (PHOTOSYNTHESIS)

Algae sequester CO2 from the atmosphere during photosynthesis and recycle it in the form of biomass (**Atwany et al., 2020**). Photosynthesis is a process that takes place in chloroplasts, by which solar energy is converted into chemical energy in the form of lipids and carbohydrates, which can further be used for producing biofuels, food, or other chemicals (**Mondal et al., 2017)**. The overall photosynthesis reaction is written as (**Zhang, 2015**) The process is

Biomass measurements and growth rates

Biomass concentration determines the carbon dioxide fixation, since an increase in the concentration does not only provide higher biomass quantity per volume of culture, but also increases the amount of carbon fixed. Algae grow at different growth rates, the growth kinetics takes into account the different culture parameters (**Adamczyk et al., 2016; Gautam et al., 2015**). For micro algae. The Impact of Greenhouse Gases on the Environmental Situation in the World Continuous climate change is driven by rising emissions of carbon dioxide, the main component of greenhouse gases. The sources of carbon dioxide emissions include fossil fuels (oil, coal, peat, gas) and waste (animal husbandry, agriculture). Atmosphere of N2O, CH4, and CO2have increased by 20%, 150%, and 40% since 1750,respectively (**Gautam et al., 2015**). Parts of gas emissions in various energy-intensive industries are shown in Table

Table 1. Parts of gas emissions in various energy-intensive industries.

%	NOx	SO2	SO3	CO	SPM	CO2	CH4	N2O
Domesticated	6.6	7.0	8.6	0.9	1.8	25	7.3	4.2
Industry	9.3	22.2	32.1	0.4	2.8	16.6	4.1	2.6
Transport	48.4	28.7	30.6	96.6	86.8	23.4	79.7	47.9
Agriculture	3.9	5.4	3.2	0.2	4.7	2.6	1.4	40.4
Oil Refineries	NA	NA	NA	NA	NA	3.2	0.7	0.4
Power Plant	31.8	36.7	25.5	1.7	3.9	29.1	6.7	4.4

TAKEN FROM- **Tatyana Iglina , Pavel Iglin and Dmitry Pashchenko MARCH 2022 (DOI:10.3390/su14073801)**

The problem of global warming and greenhouse gases is already directly affecting world energy and production. In the future, the impact of CO2emissions will only grow. Many researchers are engaged in the description of solutions to the problem of greenhouse gases (GHG). Moreover, in 2013, the Intended Nationally Determined Contributions (INDC) Agreement was signed in Paris. This agreement states that it is necessary to reduce the global temperature by 2◦C in the 21st century. The main negative effects of climate change due to GHG emissions on the planet are presented in Table 2.If we compare the CO2emissions of the countries of the world economies for 2016 and2019, we can see a directing a slight decrease in carbon dioxide emissions. For example, the share of CO2emissions from China in 2019 was 28.8% of the total emissions compared to 29.3% in 2016. These data allow us to conclude that more developed countries have already embarked on the path of capturing CO2 to preserve the climate. However, at the moment, the methods of capturing CO2have been scarcely researched, despite the existence of a wide range of publications on this topic.

7. ALGAE PRODUCTION: HISTORY, PRESENT, AND FUTURE

Algae encompass a diverse group of organisms originating from four distinct biological kingdoms: Bacteria, Plantae, Chromista, and Protozoa. While approximately 44,000 species have been formally described, the true number likely surpasses this figure, potentially reaching up to a million species, depending on the definition of "algae" employed (**Guiry 2012**). As primary producers in aquatic ecosystems, algae serve as the foundation of many food chains. Their exceptional biomass productivity, often surpassing that of terrestrial plants, and their ability to thrive in freshwater or marine environments without the need for antibiotics or pesticides have fueled growing consumer demand and commercial interest in algae cultivation over recent decades.

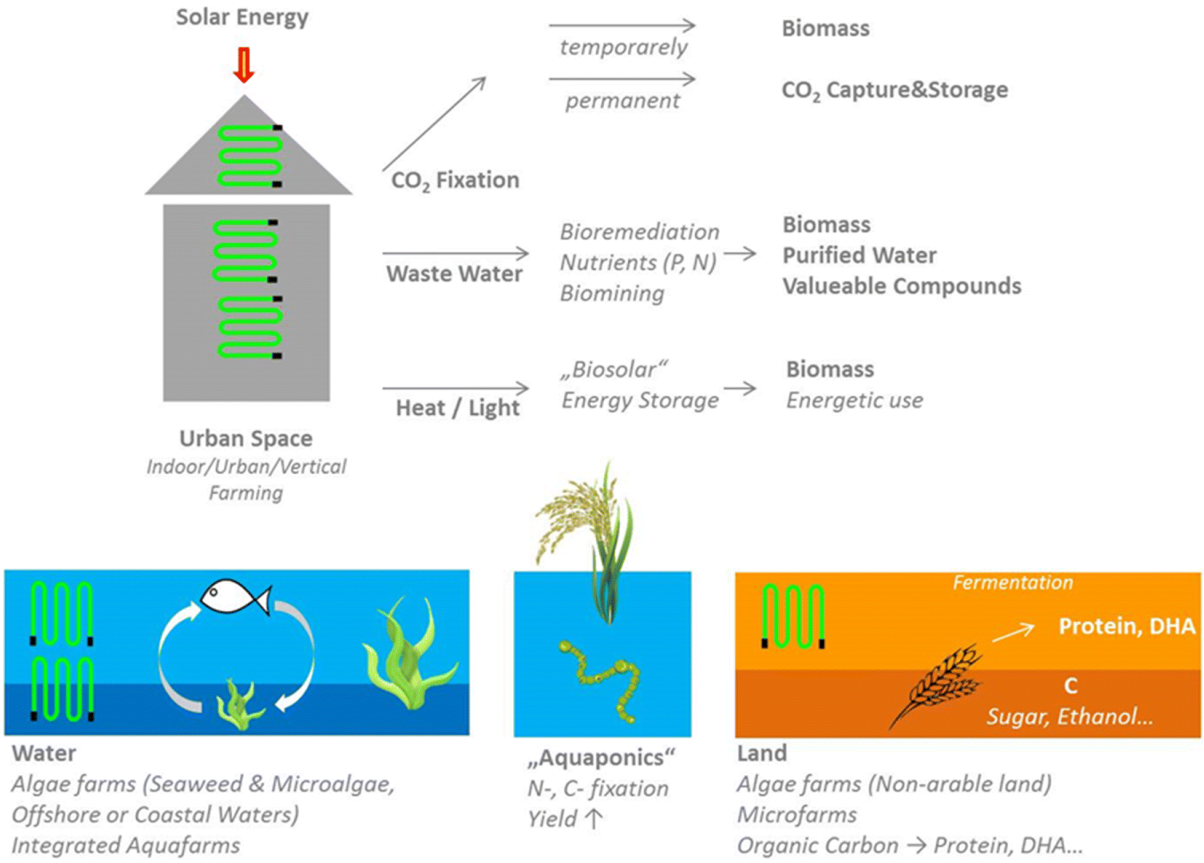
Seaweeds have a rich history of utilization as food and medicine, dating back at least 14,000 years, with evidence suggesting they may have played a role in the peopling of the Americas **(Erlandson et al. 2007)**. The cultivation of seaweeds for agricultural purposes in East Asia can be traced back to at least 1640, if not earlier (**Ferdouse et al. 2018; Pulz and Gross 2004**). In contrast, the consumption of microalgae has historically been rare, with notable exceptions such as the harvesting of Spirulina, a type of cyanobacteria, by the Aztec people in Mexico and the Kanembu people near Lake Chad **(Ahsan et al. 2008)**. The large-scale cultivation of microalgae and seaweeds emerged relatively recently, beginning in the mid-twentieth century when global industrial algae production was virtually nonexistent. One of the earliest instances of commercial microalgae cultivation involved Chlorella vulgaris in Japan during the 1960s (**Mobin and Alam 2017**). By 2004, global microalgae production was estimated at around 5000 tons (dry weight), with an annual market value of approximately US$ 1.25 billion (**Pulz and Gross 2004**). While precise data on current production levels are scarce, it is evident that both microalgae and seaweed production have experienced significant growth. The Food and Agriculture Organization (FAO) reports that global seaweed production more than doubled from 14.7 million tons (wet weight) in 2005 to 30.4 million tons in 2015, representing a market worth approximately US$ 6 billion (**Ferdouse et al. 2018; Camia et al. 2018**). Despite this growth, seaweed and microalgae production remain minuscule compared to global agricultural output, which exceeds 1.6 trillion tons annually (**Buschmann et al. 2017**).

Of the 220 seaweed species commercially utilized, the majority are cultivated offshore in marine environments, with only around 1.1 million tons harvested from the wild—an amount that has remained relatively stable in recent years (**Ferdouse et al. 2018**). Most cultivated seaweed is either consumed directly as human food (roughly 47%) or used in the production of hydrocolloids, such as agar, carrageenan, and alginate, which account for over 50% of seaweed usage (**Buschmann et al. 2017**). Productivity rates for various seaweed species cultivated offshore in Japan

range from 1.3 kg/m2 for Laminaria angustata to 8.3 kg/m2 for Sargassum macrocarpum, comparable to land crop productivity (**Notoya 2010**). According to estimates by the World Bank **(Bjerregaard et al. 2016**), seaweed cultivation could potentially span 5 million km2 of marine environments.

Production area—roughly 0.3% of the ocean surface—would be enough to produce as much biomass as is produced in all of global agriculture annually.

Even though microalgae are spatially more productive than terrestrial plants and macroalgae—Spirulina, for example, produces about 10 times more biomass per hectare than high-yielding corn hybrids (**Dismukes et al. 2008**)—their production is still more expensive, especially due to high initial investment and production costs. For this reason, microalgae production is mainly focused on the provision of "low-volume, high-value" products, such as β-carotene, astaxanthin, docosahexaenoic acid, docosahexaenoic acid, phycobilin pigments, and algal extracts for use in cosmetics, instead of "high-volume, low-value" products, such as biofuel, food, or feed (**Borowitzka 2013**). The same goes for seaweeds, which some also view as ideal crops for biofuel production, due to high carbohydrate contents of roughly 50%. With fossil oil prices being as low as they are, there is at the moment little chance of competitiveness. One way of overcoming this problem in the case of microalgae production is either the development of a scalable phototrophic production technology or the development of a convincing bio refinery concept for the multiple use of the algal biomass. Light limitation and technological limits are the most challenging tasks. The other approach is focused on the monetarization of ecosystem services that algae can provide: the cleaning of water, the mitigation of climate change, etc. This approach, though promising, requires significant changes in the legislative set-up of the economic system and is thus highly controversial. In the following passage, we want to delve deeper into these problems and outline a way forward.



Potential of algae for a circular bio economy, landless food production, and urban farming

(TAKEN FROM- **Jörg Ullmann & Daniel Grimm 21 January 2021**

DOI - https://doi.org/10.1007/s13165-020-00337-9)

8. ALGAE CULTIVATION

Depending on the species and growth conditions, a wide range of different macromolecules, such as lipids, carbohydrates and proteins, can be identified in algae. Lipids that build cell membranes of algal cells are molecules with long carbon chains in their structure. An increased lipid content reduces the specific gravity, allowing algae cells to float on the surface of water bodies. A floating algae cell moves towards a source of solar energy. Algae species vary in lipid content from 20 to 80% (dry weight dw). Lipids extracted from microalgae can be used to produce biodiesel. Lipid extraction residues contain mainly carbohydrates and proteins. In contrast, carbohydrates such as starch and other sugars can be fermented to produce ethanol. Ethanol production, as a key step in the transesterification process, can facilitate the oil extraction process for biodiesel production. Ethanol and sodium ethoxide serve as catalysts in the oil trancesterification process. Various species of microalgae have the ability to synthesize and accumulate a significant part of their dry matter in the form of lipids, as shown in Table 1. Often, as a result of environmental stress, e.g., limiting the amount of nitrogen, phosphorus, silicon or high salinity, the amount of lipids in

algae increases. The speed and intensity of lipid synthesis in cells also depend on their growth phase.

Table 2. Lipid content of selected algae species presented as dry weight percentage

Algae Species	Lipids (% dw)
Scenedesmus obliquus	11–22/35–55
Scenedesmus dimorphus	6–7/16–40
Botryococcus brauni	25–75
Chlorella sp.	28–32
Chlorella vulgaris	14–40/56
Chlorella protothecoides	23/55
Chlorella emersonii	63
Chlorella minutissima	57
Chlorella sorokiana	22
Spirulina maxima	4–9
Neochloris oleoabundans	35–65

When it comes to carbohydrates, the main group of compounds is polysaccharides, which perform reserve and structural functions in algae cells. Starch and glycogen are stored in plastids as storage components, while cellulose is the main structural component of the cell wall, as are sulfated polysaccharides. The type of stored carbohydrates depends on the species of alga; e.g., cyanobacteria synthesize glycogen, which is a water-soluble α-polyglucan. In contrast, green microalgae synthesize starch particles with a size of 2 to 100 μm, which consist of 72–82% amylopectin (α-1,4-glucosidic and α-1,6-glucosidic bonds) and 18–28% amylose (α-1,4-glucosidic bonds). Cellulose present in the cell wall of microalgae is also used for the production of bioethanol, which is characterized by a slightly different structure of the cell wall than the lignocellulose of land plants. The lack of lignin in algae means that pretreatment to release biodegradable organic matter does not have to be as intensive as in the case of traditional plant materials.

Algae are cultivated in a variety of aquatic systems, from open-air ponds to closed photo bioreactors with tightly controlled environments. The range of temperatures needed to support algae growth is specific to the species and strain being cultivated. The optimal temperature for phytoplankton is in the range of 20–30 °C. Temperatures lower than 16 °C slow growth, and temperatures higher than 35 °C are usually fatal to many species. Algae can be cultivated in raceway ponds, which can be open ponds and covered ponds, and in photo bioreactors. Open ponds are the most economical places to grow algae that consist of natural open ponds that can be both freshwater and saltwater ponds. These ponds can have an area of up to several hectares. The main disadvantages of such open systems are invasions of algae species other than the cultivated one, growth of fungi and contamination of selected species of microalgae. About 98% of the total algae biomass production is obtained using open pond systems, and because the growth rate of microalgae is high, they are able to produce about 15–20 tons of dry biomass per hectare per year. The oil content in the dry matter of algae can reach up to 50–60% for high-yielding varieties. This makes algae cultivation very

economical. Literature data describe different types of cultivation of microalgae species in open ponds. For example, Chlorella pyrenoidosa grown using secondary wastewater in an open pond removed excess nutrients and produced the highest biomass concentration of 1.71 g/L. Similarly, Dunaliella salina and Nannochloropsis sp. in open ponds obtained biomass productivity of 0.096 gL/d and 0.208 gL/d, respectively. Therefore, the open pond system can be used to obtain a large amount of biomass for the production of biofuels. The problems that accompany open pond cultures are solved to some extent by the use of covered ponds. Here, the uncontrolled growth of undesirable species of algae and fungi is inhibited to some extent. Another problem, which is evaporation from open ponds, is also eliminated by covering the surface of the pond. The disadvantages of covered ponds should also be mentioned. One of them is certainly an increase in temperature, which can be partly offset by mixing. Various modifications are often used to achieve the greatest possible efficiency in algae cultivation. According to Thomas et al., a microalgae culture was kept in constant motion on an inclined surface by gravity . The microalgae cultures are collected in a tank under the roof and then pumped back to the roof. High evaporation rates on sunny days and volume fluctuations on rainy days are adequately maintained in the buffer tank. Species such as Scenedesmus sp., Dunaliella salina and Nannochloropsis sp. are grown in outdoor systems.

Another type of microalgae culture is photo bioreactors, which are artificial culture system that promotes the growth of a selected strain under optimal conditions, such as light, temperature, pH, etc. Photo bioreactors are constructed in the form of various structures, including tubular, flat or vertical columns, where algae cultures are pumped and recirculated continuously. Photo bioreactors are made of transparent acrylic or glass materials, which allows photosynthesis and algae growth, thanks to access to natural sunlight. They can achieve an efficiency of up to 100 gms/m2/h. The undoubted advantages of these bioreactors as a method of algae cultivation include the possibility of avoiding contamination with foreign species of algae, bacteria and fungi; minimizing evaporation; better dissipation of heat and nutrients; the possibility of continuous monitoring of various parameters; no requirement for natural sunlight. Among the types of bioreactors most commonly used for algae cultivation, the following can be mentioned: tubular photo bioreactors, plate photo bioreactors, helical photo bioreactors, horizontal photo bioreactors, foil photo bioreactors, tubular bioreactors, flat plate bioreactors and fermenter type bioreactors.

When considering the cultivation of algae, it is important to remember to maintain basic physical conditions such as adequate lighting, temperature, the composition of the medium and the design of the bioreactor enabling continuous mixing, which determines the free flow of gases and components of the medium . Considering the importance of the composition of the algae culture medium, the potential of using liquid anaerobic digestate as a culture medium for microalgae growth was investigated and compared to three different synthetic media in terms of biomass yield, fatty acid composition and nutrient utilization/recovery. The highest nutrient efficiency rates, the highest lipid content (34%) and the highest concentrations of C16:0 (114 mg/L) and C18:0 (60.9 mg/L) were obtained when the mixed culture of microalgae was carried out in anaerobic liquid digestate. An increase in the content of polyunsaturated fatty acids (PUFA) was also observed, which is a positive and desirable

effect of changing the culture medium because the PUFA present in microalgae allows them to adapt more effectively to extreme conditions. Another medium for the growth of algae, already mentioned earlier, can be wastewater. Growing algae using wastewater and even flue gas is taking advantage of their ability and efficiency in converting CO2 and nutrients into biomass. The addition of CO2 from the flue gas increases the production of algae biomass, which also extracts nitrogen and phosphorus from the wastewater. Due to the presence of impurities, such biomass cannot be used for the production of food or feed, but it can be used for the production of bioenergy in the form of various biofuels .

Table 3. Performance of microalgae in CO_2 sequestration.

Species	CO_2 capture efficiency	Biomass Yield	Product yield	Operational condition	Source
Chlamydomonas reinhardtii	113 mg/L.d	512 mg/L	Bioethanol 0.46-0.49 g/g	Tris acetate phosphate medium, light-dark cycles of 24/0, 20-35˚C temperature, pH 6.5-7, 6 d	(Banerjee et al., 2021)
Chlorella pyrenoidosa	92%	90.25 g/d	-	Six-stage serial algal reactors, purified terephthalic acid wastewater, light-dark cycles of 12/12, 25˚C temperature, pH 4.4-7.4, 2 d	(Yang et al., 2020)
Chlorella sorokiniana UTEX1602, *Chlorella* sp. L166, *Scenedesmus* sp. 336	52.21%	900.04 mg/L	Lipid 20.82 mg/L Protein 142.12 mg/L	Batch conical flask, light-dark cycles of 24/0, 25˚C temperature, pH 6.8, 10 d	(Han et al., 2021)
Chlorella sorokiniana, Coelastrella sp., *Chlorella pyrenoidosa*	567 mg/L.d	1.1 g/L	-	Palm oil mill effluent wastewater, light-dark cycles of 24/0, 25˚C temperature, pH 7, 7 d	(Ding et al., 2020)
Chlorella sp. L166	93.7%	-	Lipid 6.89 mg/L	Hybrid low temperature plasma system, BG11 medium, 30˚C temperature, 10	(Song et al., 2021)

Species	CO_2 capture efficiency	Biomass Yield	Product yield	Operational condition	Source
				d	
Chlorella sp. L166 *Chlorella* sp. UTEX1602 *Scenedesmus* sp. *336*, and *Spirulina* sp. FACHB-439	-	1.02 g/L	Lipid 38 mg/L	Artificial brewery wastewater, light-dark cycles of 24/0, room temperature, pH 6.8-7, 10 d	(Song et al., 2020)
Chlorella sp. L166, L38 and UTEX1602	85%	-	Protein 164 mg/L Lipid 710.6 mg/L	BG11 medium supplemented with $NaNO_3$, 30˚C temperature, pH 8, 36 d	(Song et al., 2019b)
Chlorella sp. UTEX1602 and L38	76.8%	-	Lipid 15.9 mg/L	Batch feeding ammonia adsorption-microalgae hybrid system, BG11 medium, 30˚C temperature, 27 d	(Song et al., 2019a)
Chlorella vulgaris	75%	1.28 g/L	-	Open race pond, 60 L, 4 cycles, 30˚C temperature, pH 7-8, 30 d	(Yadav et al., 2020)
Chlorella vulgaris	40%	2.12 g/L	-	Belt conveyor reactor, 20:20:20 NPK media, 20-27˚C temperature, pH 7.6, 18 d	(Al Haboubi, 2021)
Chlorella vulgaris (UTEX 2714)	182 mg/L.d	0.219 g/L.d	-	Batch photobioreactor, Bold's Basal Medium, light-dark cycles of 12/12, 20-40˚C temperature, 8 d	(Hossain et al., 2022)
Desmodesmus sp.	210 mg/L.d	1.1 g/L	Lipid 419.57 mg/L	Batch photobioreactor, light-dark cycles of 12/12, pH 6.5-8, 8 d	(Premaratne et al., 2021)
Parachlorella kessleri	86.4%	65.8 mg/L.d	Lipid 11.26	Polycarbonate bubble column	(Beigbeder et al., 2021)

Species	CO_2 capture efficiency	Biomass Yield	Product yield	Operational condition	Source
			mg.L Protein 13.58 mg/L	photo bioreactors, Bold's Basal Medium, light-dark cycles of 16/8, room temperature, pH 8.5, 14 days	
Spirulina platensis	-	9.1 g/m^3	-	BIOCOIL photobioreactor, liquid medium broth, 40 d	(Concas et al., 2010)
Spirulina platensis	178.46 mg/L/d	1.75 g/L	Lipid 58.42 mg/L	Hybrid adsorption and conversion system, Zarrouk medium, light-dark cycles of 24/0, pH 8.5-11, 18 d	(Li et al., 2020)

9. ALGAE CULTIVATION METHODS

Algal cultivation refers to the process of growing algae for various purposes, including carbon capture, biofuel production, wastewater treatment, and food supplements. Several methods and systems are used for algal cultivation, each with its advantages and challenges. Here are the main methods of algal cultivation:

1. **Open Ponds:** Open pond systems are the simplest and most cost-effective method of algal cultivation. These ponds are shallow, lined with plastic or concrete, and exposed to sunlight. Algae are cultivated in the ponds, where they capture CO2 from the atmosphere and nutrients from the water. Open ponds require large land areas and are susceptible to contamination and temperature fluctuations but are suitable for large-scale production.
   (Borowitzka LJ, Borowitzka MA,1990). This cultivation method heavily relies on naturally occurring water bodies to provide the right conditions and nutrients for the growth of microalgae. Currently, one of the largest commercial microalgae cultivation facilities in natural water is situated at Hutt Lagoon, Australia. This facility is capable of producing 6 tons of β-carotene annually from Dunaliella using its 700-hectare ponds**.(Hamed I, 2016).**

2. **Closed Photo bioreactors (PBRs):** Closed photo bioreactors are enclosed systems that provide controlled conditions for algal growth. These systems can be made of glass or plastic and are equipped with pumps, mixers, and lighting systems to optimize algal productivity. Closed PBRs offer advantages in terms of contamination control, temperature regulation, and CO2 capture efficiency but are more expensive to build and operate than open ponds (**Tamburic B, Zemichael FW, 2011**). Commercial usage of the photo bioreactor design described has yet to be widespread, although numerous large-scale experimental reactors have been constructed. For example, a 40-liter vertical column outdoor photo bioreactor was utilized for the cultivation of Chlorella zofingiensis in Guangdong, China**.(Huo S, Wang Z at all, 2018).**

3. **Raceway Ponds:** Raceway ponds are large, circular or oval-shaped ponds with paddlewheels or pumps to circulate the algal culture. They are similar to open ponds but have a more controlled flow regime to enhance mixing and light distribution. Raceway ponds are intermediate in cost and complexity between open ponds and closed PBRs and are suitable for medium-scale algal cultivation.

4. **Vertical Photo bioreactors:** Vertical photo bioreactors are columnar or tubular systems that allow for high-density algal cultivation in a small footprint. Algal culture flows through transparent tubes or panels, where it is exposed to light and supplied with nutrients and CO2. Vertical photo bioreactors offer advantages in terms of space efficiency, scalability, and productivity but are more complex and expensive to operate than other systems.

5. **Floating Algal Systems:** Floating algal systems involve cultivating algae on floating platforms or structures in natural or artificial water bodies, such as ponds, lakes, or coastal areas. These systems utilize the natural mixing and nutrient supply of the water body while minimizing land use. Floating algal systems can be combined with other activities such as wastewater treatment or aquaculture to enhance resource efficiency**.(Laamanen CA, Ross GM, 2016**) Flotation employs small bubbles that adhere to microalgae cells, facilitating their flotation to the surface of the culture media for easy harvesting. This method offers several advantages, including relatively high harvesting efficiency, straightforward operating procedures, and high processing throughput at low cost.(**Ndikubwimana T, Chang J, 2016**).

6. **Algal Turf Scrubber (ATS):** ATS systems use algal mats or turf to capture nutrients and pollutants from agricultural runoff or wastewater. Algae grow on an inclined surface or mesh, where they absorb nutrients and CO2 from the water. The algal biomass can then be harvested and utilized for various purposes, while the cleaned water is discharged or recycled.

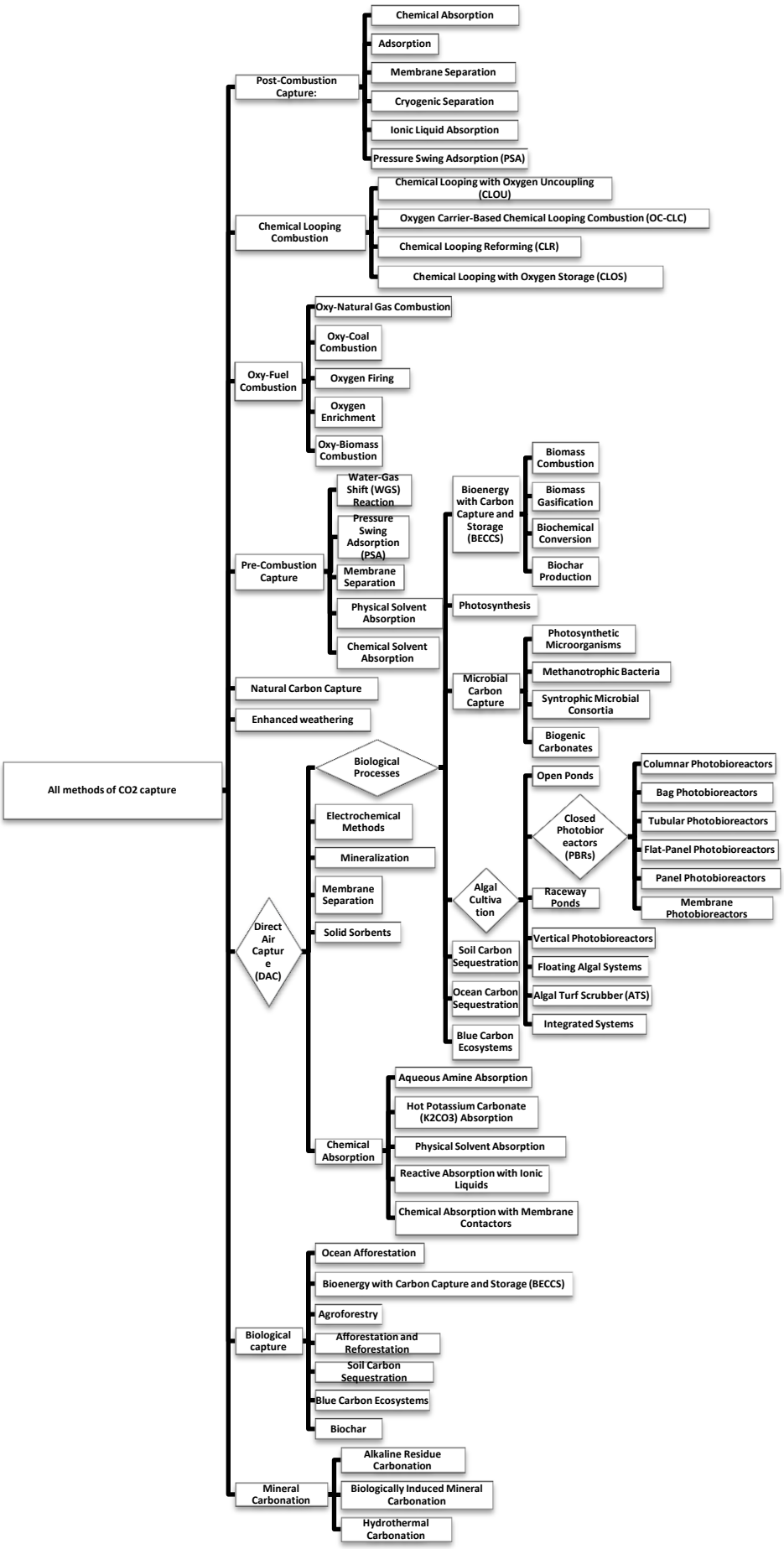
7. **Integrated Systems:** Integrated algal cultivation systems combine different cultivation methods and technologies to optimize productivity and resource efficiency. For example, closed PBRs can be integrated with wastewater treatment facilities to capture nutrients and CO2 from wastewater while producing algae for biofuel or bio products. Integrated systems offer synergistic benefits and can enhance the sustainability and economic viability of algal cultivation.

Table 4. Different types of algae cultures cultivation conditions depend on selected factors.

Factor	Cultivation Conditions	Algae Species	Refernces
Culture Medium	BG-11 and Chu 13 media with CO2 supplementation	*Botryococcus braunii, Scenedesmus obtusiusculus*	Ge, Y.; Liu, J at all 2011 Toledo-Cervantes, A.; Morales at all 2013
	synthetic media with organic carbon sources	*Pediastrm sp., Micractinium sp., Ankistrodesmus falcatus, Monoraphodium sp., Desmodesmus sp., Coleastrum sp. Mucidosphaerium sp*	Zheng, S.; Zou, S. at all 2022, Mehrabadi, A.; Craggs at all 2016,
	nitrogen-rich media or nitrogen limiting media	*Chlorella vulgaris ESP-31*	Barua, V.B.; Munir, M. at all 2021
Lighting	50–200 µmol·m/s	*Chlorella vulgaris*	Chávez-Fuentes, P.; Ruiz-Marin, at all 2018 Khalili, A.; Najafpour, at all 2015
	red light	*Arthrospira (Spirulina) platensis*	Markou, G. 2014
	High- and low-intensity green LEDs	*Brachiomonas submarina, Scenedesmus obliquus*	McGee, D.; Archer, at all 2020 Ho, S.-H.; Chan, at all 2014 Gim, G.H.; Ryu, J at all 2016,
	High-intensity blue	*Rhodella sp.,*	McGee, D.; Archer, at

	and white LED	*Stauroneis sp.*	all 2020 Gim, G.H.; Ryu, J at all 2016,
Temperature	20 °C	*Enteromorpha sp.*	Sousa, A.I.; Martins, at all 2007
	25 ± 1 °C	*Botryococcus strain SK*	Yeesang, C.; Cheirsilp, B. 2011
	25 °C	*B. braunii 765*	Yoshimura, T.; Okada, S.; at all 2013
	10–30 °C	*Scenedesmus sp.*	Li, X.; Hu, at all 2011

The temperature range in which microalgae can be grown is from 10 to 40 °C. Above this temperature range, cells die, and below this, they do not follow the correct growth curve. Lighting is the most important parameter for the development and growth of algae in bioreactors. Algae can carry out photosynthesis in the range of 400–700 nm. It should also be remembered that excessive sunlight intensity causes photo-oxidation of microalgae, which reduces their productivity. The cell density in the culture is directly proportional to the growth rate of the algae. However, low stocking densities are preferred in open pond systems. On the other hand, in a flat plate or tubular bioreactors, higher culture density is quite well tolerated due to better mass transfer and light distribution. Another key factor affecting algae biomass production is the availability of CO2 and nutrients. Too much oxygen inhibits the growth of algae, which is why bioreactors carry out continuous bio monitoring of the level of gases and nutrients contained in the culture broth. Continuous mixing of the cultures should also be applied to ensure uniform growth and even distribution of nutrients in the culture broth. This is, of course, impossible for open ponds, but for different types of bioreactors, it is a key factor in the efficiency of algae cultivation. Mixing has a significant effect on light, CO2 and nutrient availability. Photo bioreactors have major advantages over open pond systems in terms of preventing water loss, preventing foreign strain invasion, proximity and nutrients, light and CO2


All methods of CO2 capture
Post-Combustion Capture:
Chemical Absorption
Adsorption
Membrane Separation
Cryogenic Separation
Ionic Liquid Absorption
Pressure Swing Adsorption (PSA)
Chemical Looping Combustion
Chemical Looping with Oxygen Uncoupling (CLOU)
Oxygen Carrier-Based Chemical Looping Combustion (OC-CLC)
Chemical Looping Reforming (CLR)
Chemical Looping with Oxygen Storage (CLOS)
Oxy-Fuel Combustion
Oxy-Natural Gas Combustion
Oxy-Coal Combustion
Oxygen Firing
Oxygen Enrichment
Oxy-Biomass Combustion
Pre-Combustion Capture
Water-Gas Shift (WGS) Reaction
Pressure Swing Adsorption (PSA)
Membrane Separation
Physical Solvent Absorption
Chemical Solvent Absorption
Natural Carbon Capture
Enhanced weathering
Direct Air Capture (DAC)
Biological Processes
Electrochemical Methods
Mineralization
Membrane Separation
Solid Sorbents
Chemical Absorption
Aqueous Amine Absorption
Hot Potassium Carbonate (K2CO3) Absorption
Physical Solvent Absorption
Reactive Absorption with Ionic Liquids
Chemical Absorption with Membrane Contactors
Biological capture
Ocean Afforestation
Bioenergy with Carbon Capture and Storage (BECCS)
Agroforestry
Afforestation and Reforestation
Soil Carbon Sequestration
Blue Carbon Ecosystems
Biochar
Mineral Carbonation
Alkaline Residue Carbonation
Biologically Induced Mineral Carbonation
Hydrothermal Carbonation
Bioenergy with Carbon Capture and Storage (BECCS)
Biomass Combustion
Biomass Gasification
Biochemical Conversion
Biochar Production
Photosynthesis
Microbial Carbon Capture
Photosynthetic Microorganisms
Methanotrophic Bacteria
Syntrophic Microbial Consortia
Biogenic Carbonates
Algal Cultivation
Open Ponds
Closed Photobioreactors (PBRs)
Columnar Photobioreactors
Bag Photobioreactors
Tubular Photobioreactors
Flat-Panel Photobioreactors
Panel Photobioreactors
Membrane Photobioreactors
Raceway Ponds
Vertical Photobioreactors
Floating Algal Systems
Algal Turf Scrubber (ATS)
Integrated Systems
Soil Carbon Sequestration
Ocean Carbon Sequestration
Blue Carbon Ecosystems

10. CATALYSTS:

A catalyst is a substance that speeds up the rate of a chemical reaction without being consumed in the process. It works by providing an alternative pathway for the reaction to occur, typically by lowering the activation energy required for the reaction to proceed. Catalysts enable reactions to occur more quickly or at lower temperatures, making them essential in various industrial processes and biochemical reactions.

1) **Catalysts can be divided into two main types:**
   1.1. **Homogeneous catalysts:** These are in the same phase as the reactants. They are typically dissolved in the same solvent as the reactants. For example, in the reaction between hydrogen peroxide (H_2O_2) and iodide ions (I^-) to produce water and iodine, the iodide ions act as a homogeneous catalyst.
   1.2. **Heterogeneous catalysts:** These exist in a different phase from the reactants. They are often solid materials that the reactants are in contact with. For example, the catalytic converters in cars contain solid metal catalysts such as platinum, palladium, and rhodium, which facilitate the conversion of harmful pollutants into less harmful substances.

   Catalysts play a crucial role in numerous industrial processes, including the production of fuels, chemicals, and pharmaceuticals, as well as in environmental protection by facilitating the cleanup of pollutants. Additionally, they are essential in biological systems, where enzymes act as catalysts to drive biochemical reactions necessary for life.

2. **What is Nano Catalysts ?**

   Nano catalysts, also known as or nanoparticle catalysts, are catalysts that are comprised of nano scale particles, typically with dimensions ranging from 1 to 100 nanometers. These catalysts offer unique properties and advantages compared to their bulk counterparts due to their small size and high surface area-to-volume ratio.

3. **Some key characteristics and advantages of nano catalysts include:**

   • **High surface area**: Nano catalysts have an exceptionally high surface area-to-volume ratio compared to bulk catalysts. This increased surface area provides more active sites for catalytic reactions, leading to enhanced catalytic activity.

   • **Improved reactivity**: The high surface area and unique surface structures of nano catalysts can lead to improved reactivity and selectivity in catalytic reactions. This can result in higher reaction rates, improved yields, and better control over reaction pathways.

   • **Tunable properties:** The properties of nano catalysts, such as composition, size, shape, and surface chemistry, can be finely tuned and controlled during synthesis. This tunability allows for optimization of catalyst performance for specific reactions and applications.

- **Reduced catalyst loading**: Nano catalysts often require lower catalyst loadings compared to bulk catalysts while maintaining high catalytic activity. This can result in cost savings and reduced environmental impact in industrial processes.

- **Novel catalytic mechanisms:** Nano catalysts may exhibit unique catalytic mechanisms that differ from those of bulk catalysts due to quantum size effects and confinement effects at the nano scale. These novel mechanisms can lead to the development of new catalytic processes and materials

4. NANO PARTICAL MAKING PROCESS

Creating nanoparticles involves various techniques tailored to the specific properties and applications of the particles. Here's an overview of some common methods:

4.1. Chemical Precipitation: In this method, a precursor solution containing metal salts or other compounds is mixed with a reducing agent or precipitating agent under controlled conditions (temperature, pH, stirring rate). The reaction results in the formation of nanoparticles as the precursor compounds are reduced or precipitated out of solution. Examples include the synthesis of metal nanoparticles like gold, silver, and platinum.

4.2. **Sol-Gel Synthesis**: Sol-gel synthesis involves the hydrolysis and condensation of metal alkoxides or other precursors to form a colloidal suspension or gel. The resulting gel is then subjected to drying and calcination to form nanoparticles. This method is commonly used to produce metal oxide nanoparticles such as silica, titania, and alumina.

4.3. Chemical Vapor Deposition (CVD): CVD involves the decomposition of volatile precursor molecules in the gas phase to deposit nanoparticles onto a substrate. The precursor molecules are introduced into a reactor chamber along with a carrier gas and then decomposed by heat or plasma. Nanoparticles are deposited on the substrate surface or within the reactor chamber, depending on the specific conditions. This method is used for producing semiconductor nanoparticles like quantum dots and carbon nanotubes.

4.4. Physical Vapor Deposition (PVD): PVD techniques, such as sputtering and evaporation, involve the physical deposition of material from a solid source onto a substrate. Nanoparticles can be produced by controlling the deposition parameters, such as temperature, pressure, and deposition rate. This method is commonly used for producing metallic nanoparticles and thin films.

4.5. Micro emulsion Synthesis: Micro emulsion synthesis involves the use of surfactant-stabilized micro emulsions as reaction media for nanoparticle synthesis. Precursor compounds are dissolved in the water-in-oil micro emulsion, and chemical reactions occur within the confined spaces of the micelles. Nanoparticles are formed as the reaction progresses, and they are stabilized by the surfactant molecules. This method is suitable for producing nanoparticles with controlled size, shape, and surface properties.

4.6. **Electrochemical Deposition**: Electrochemical deposition involves the reduction of metal ions from an electrolyte solution onto an electrode surface.By controlling the applied potential, current density, and deposition time, nanoparticles can be formed with precise control over size and morphology. This method is commonly used for producing metallic nanoparticles and thin films.

4.7. Biosynthesis: Some nanoparticles can be synthesized using biological organisms, such as bacteria, fungi, or plants, as natural templates or reducing agents. Biological systems can produce nanoparticles through enzymatic reactions or extracellular processes. This method offers environmentally friendly and sustainable approaches to nanoparticle synthesis.

5. Why Nano partical making from plant extract is best method ?

Using plant extracts to produce nanoparticles can be advantageous for several reasons:

- **Biocompatibility:** Plant extracts are often biocompatible and non-toxic, making them suitable for various biomedical applications. When used in medicine, they are less likely to cause adverse reactions or side effects.

- **Eco-friendly:** Plant extracts are derived from renewable resources, making them environmentally friendly compared to synthetic chemicals. This approach reduces the reliance on harsh chemicals and minimizes the environmental impact of nanoparticle production.

- **Cost-effective**: Plant extracts are typically abundant and readily available, which can make them a cost-effective option for nanoparticle synthesis. This can be particularly beneficial for industries looking to scale up production without incurring high costs.

- **Functional properties**: Plant extracts often contain a variety of bioactive compounds such as polyphenols, flavonoids, and terpenoids, which can confer specific functional properties to the nanoparticles. These properties may include antioxidant, antimicrobial, anti-inflammatory, or anticancer activities, depending on the plant species and extraction method used.

- **Biodegradability:** Nanoparticles synthesized from plant extracts are often biodegradable, meaning they can be broken down naturally over time. This characteristic is advantageous for applications where the nanoparticles need to degrade after fulfilling their purpose, such as in drug delivery systems or environmental remediation.

- **Versatility**: Plant extracts offer a wide range of possibilities for nanoparticle synthesis due to the vast diversity of plant species and the different compounds they contain. This versatility allows researchers to tailor nanoparticle properties such as size, shape, and surface characteristics to suit specific applications.

Overall, utilizing plant extracts for nanoparticle synthesis offers a sustainable, cost-effective, and biocompatible approach with potential applications across various fields, including medicine, agriculture, and environmental science.

6. Nano partical from plant extract

Creating nanoparticles from plant extracts involves utilizing the phytochemicals present in plants as reducing agents and stabilizers for nanoparticle synthesis. Here's a simplified explanation of the process:

- **Selection of Plant Extract:**

Plants contain various bioactive compounds, such as polyphenols, flavonoids, and alkaloids, which can act as reducing and stabilizing agents for nanoparticle synthesis.

Different plant extracts may contain different types and concentrations of phytochemicals, leading to variations in the properties of the synthesized nanoparticles.

- **Preparation of Plant Extract:**

The selected plant material, such as leaves, seeds, or roots, is collected and processed to extract the bioactive compounds.

Extraction methods may involve grinding the plant material, followed by solvent extraction or other techniques to obtain a concentrated extract rich in phytochemicals.

- **Nanoparticle Synthesis:**

The plant extract is mixed with an aqueous solution containing metal salts (e.g., silver nitrate, gold chloride) or other precursor compounds.

Phytochemicals in the plant extract act as reducing agents, converting the metal ions into nanoparticles.

At the same time, phytochemicals may also act as stabilizing agents, preventing the nanoparticles from agglomerating or undergoing further growth.

- **Characterization:**

The synthesized nanoparticles are characterized using analytical techniques to determine their size, shape, composition, and surface properties.

Common characterization techniques include transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray diffraction (XRD), and UV-visible spectroscopy.

- **Applications:**

Nanoparticles synthesized from plant extracts have various potential applications in biomedicine, agriculture, environmental remediation, and nanotechnology.

For example, silver nanoparticles synthesized using plant extracts have antimicrobial properties and can be used in wound dressings, food packaging, and water purification.

- **Advantages:**

Utilizing plant extracts for nanoparticle synthesis offers several advantages, including sustainability, biocompatibility, and cost-effectiveness.

Plant-based synthesis methods are environmentally friendly and do not require harsh chemicals, making them suitable for green chemistry applicationns.

TABLE-5 Chemical compunds from plant extract:-

COMPOUND	FINDING IN PLANTS
Chlorogenic acid	Apple, Carrot, Coffee Beans, Graps, Potatoes, Tea Leaves
Luteolin	Celery, Parsley, Brocooli, Onion Leaves, Carrot, Peppers, Cabbages, Apple skin
Tanins	Black Berries, Pomegranates
Ferulic Acid	Rice, wheat, Pineapple, Bananas, Spinach, Beetroot, Coffee Beans, Peanut
Salicylic Acid	Tomatoes, Apple, Avocado, Cherries, Graps
Caffeic Acid	Coffee, Potatoes, Sunflower Seeds
Gallic acid (3,4,5-Trihydroxibenzoic Acid)	Tea Leaves, Orange, Graps
Proto Catechulic Acid	Dried flower of hibiscus, Carrots
Vanilic Acid	Tea, Coffee
Saponins	Garlic, Onion, Oats, Tomatoes, Spinach
Poly Saccarids	Tea
Anthocyanin	Eggplant peel, Cheery, Sweet Potatoes, Pomegranate, Strawberries

11. PHOTOSYNTHESIS AND PHOTO CATALYSTS AS SUSTAINABLE ENERGY SOLUTIONS

(Hashimoto et al.,2019) highlighted a significant development in photo catalysis attributed to **Fujishima and Honda** in the 1970s, known as the Honda-Fujishima effect. This effect laid the groundwork for various applications, including water splitting, a common type of photo catalysis.

In water splitting, sunlight interacts with nanoparticle (NP) catalysts, such as titanium dioxide (TiO_2) NPs, to split water molecules (H_2O) into oxygen (O_2) and hydrogen (H_2) atoms. This process yields hydrogen gas (H_2), which serves as an eco-friendly energy resource.

The efficiency of the water splitting process depends on nanocatalysts' ability to collect light and convert it into chemical energy for water molecules. Titanium dioxide nanoparticles are particularly effective in this regard due to their transparency to visible light and their ability to catalyze the water splitting reaction under sunlight.

Here's a simplified explanation of the water splitting process:

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$$

In this reaction, sunlight energy is absorbed by the nanoparticle catalyst (such as TiO_2), exciting electrons to a higher energy state. These energized electrons can then participate in the water splitting reaction, where water molecules are broken down into hydrogen and oxygen atoms.

12. METHANE FORMATION

Methane production from algae involves various biological and chemical processes. Here are several methods commonly used for methane production from algae:

Anaerobic Digestion: Anaerobic digestion is a biological process in which microorganisms break down organic matter in the absence of oxygen, producing biogas as a byproduct. Algal biomass, rich in organic content, can be digested by anaerobic microorganisms to produce methane (CH4) along with carbon dioxide (CO2) and other gases. This process can be carried out in anaerobic digesters or bioreactors under controlled conditions of temperature, pH, and retention time.

Biogasification: Biogasification is a thermochemical process that converts organic matter into synthesis gas (syngas) containing methane, carbon monoxide, and hydrogen. Algal biomass can be subjected to high temperatures in the presence of steam or a gasifying agent to produce syngas. The syngas can then be further processed through catalytic reactions to enhance methane yield.

Hydrothermal Liquefaction (HTL): Hydrothermal liquefaction is a thermochemical process that converts wet biomass, including algae, into biocrude oil and gas. Algal biomass is subjected to high temperature and pressure in the presence of water, which breaks down the organic matter into hydrocarbons, including methane. The produced biocrude oil can be further refined, while the gas phase can contain methane along with other gases.

Microbial Methanogenesis: Methanogenic microorganisms naturally present in anaerobic environments can directly convert organic matter, including algal biomass, into methane through a process called methanogenesis. Algal biomass can be subjected to microbial fermentation under anaerobic conditions to produce methane. This method can be enhanced through the use of specialized microbial consortia or genetically engineered microorganisms.

Algae-Microbial Fuel Cells (AMFCs): Algae-Microbial Fuel Cells combine algal photosynthesis with microbial electrochemical processes to produce methane. Algal biomass generates organic compounds through photosynthesis, which can be used as substrates for microbial metabolism in the anode chamber of the fuel cell. Microbes in the fuel cell anaerobically degrade organic compounds, producing electrons that are transferred to the anode, generating electrical current and methane as a byproduct.

Direct Methane Production from Algal Lipids: Algal lipids, extracted from algal biomass, can be subjected to catalytic processes such as pyrolysis or hydrogenation to directly produce methane. This method involves the thermal or chemical decomposition of algal lipids into smaller hydrocarbons, which can be subsequently

converted into methane. While electrolysis of water followed by the Sabatier reaction is one method to produce methane, there are other methods as well. Here are a few alternative methods for methane formation using electrolysis:

Electrolysis of Carbonate Solutions: In this method, carbonate solutions (such as sodium carbonate or potassium carbonate) are electrolyzed instead of water. Carbonate ions (CO_3^{2-}) are reduced at the cathode to produce carbon dioxide (CO_2) and oxygen (O_2):

$CO_3^{2-} + H_2O \rightarrow CO_2 + OH^- + e^-$

The generated carbon dioxide can then be used in subsequent reactions, such as the Sabatier reaction, to produce methane.

Electrolysis of Organic Compounds:

Organic compounds containing carbon and hydrogen can undergo electrolysis to produce methane. For example, electrolysis of acetic acid (CH3COOH) can yield methane along with other products:

$2CH_3COOH \rightarrow CH_4 + CO_2 + 2H_2O$

Electrochemical Reduction of Carbon Dioxide (ERC): This method involves the direct electrolysis of carbon dioxide (CO_2) to produce methane. Carbon dioxide is reduced at the cathode to form methane (CH_4) and other carbon-containing compounds. This process typically requires high-energy input and specialized catalysts to improve efficiency and selectivity.

Solid Oxide Electrolysis Cells (SOEC): Solid oxide electrolysis cells can be used to directly convert carbon dioxide and water vapor into syngas, a mixture of hydrogen and carbon monoxide. The syngas produced can then undergo further reactions, such as Fischer-Tropsch synthesis, to produce methane. This method offers potential for efficient methane production with high selectivity.

Microbial Electrosynthesis (MES): Microbial electrosynthesis involves using electrochemically active microorganisms to convert carbon dioxide into methane or other organic compounds. Microbes such as methanogenic archaea can be stimulated by supplying electrons from an electrode, leading to the reduction of carbon dioxide to methane. This method has the advantage of using renewable electricity and can potentially be integrated with wastewater treatment or biogas production processes.

Each of these methods has its own advantages and challenges, and the choice of method depends on factors such as the availability of feedstocks, energy requirements, process efficiency, and environmental considerations.

13. ALL METHODS OF METHANE PRODUCTION FROM ALGAE

Methane production from algae involves various biological and chemical processes. Here are several methods commonly used for methane production from algae:

Anaerobic Digestion: Anaerobic digestion is a biological process in which microorganisms break down organic matter in the absence of oxygen, producing biogas as a byproduct. Algal biomass, rich in organic content, can be digested by anaerobic microorganisms to produce methane (CH4) along with carbon dioxide (CO2) and other gases. This process can be carried out in anaerobic digesters or bioreactors under controlled conditions of temperature, pH, and retention time. **Biogasification: Biogasification** is a thermochemical process that converts organic matter into synthesis gas (syngas) containing methane, carbon monoxide, and hydrogen. Algal biomass can be subjected to high temperatures in the presence of steam or a gasifying agent to produce syngas. The syngas can then be further processed through catalytic reactions to enhance methane yield. **Hydrothermal Liquefaction (HTL):** Hydrothermal liquefaction is a thermochemical process that converts wet biomass, including algae, into bio crude oil and gas. Algal biomass is subjected to high temperature and pressure in the presence of water, which breaks down the organic matter into hydrocarbons, including methane. The produced biocrude oil can be further refined, while the gas phase can contain methane along with other gases. **Microbial Methanogenesis:** Methanogenic microorganisms naturally present in anaerobic environments can directly convert organic matter, including algal biomass, into methane through a process called methanogenesis. Algal biomass can be subjected to microbial fermentation under anaerobic conditions to produce methane. This method can be enhanced through the use of specialized microbial consortia or genetically engineered microorganisms. **Algae-Microbial Fuel Cells (AMFCs):** Algae-Microbial Fuel Cells combine algal photosynthesis with microbial electrochemical processes to produce methane. Algal biomass generates organic compounds through photosynthesis, which can be used as substrates for microbial metabolism in the anode chamber of the fuel cell. Microbes in the fuel cell anaerobically degrade organic compounds, producing electrons that are transferred to the anode, generating electrical current and methane as a byproduct.

Direct Methane Production from Algal Lipids: Algal lipids, extracted from algal biomass, can be subjected to catalytic processes such as pyrolysis or hydrogenation to directly produce methane. This method involves the thermal or chemical decomposition of algal lipids into smaller hydrocarbons, which can be subsequently converted into methane.

14. APPLICATION

Microalgae as a Way of Capture and Utilization of CO2 (CCU)

Utilization of captured CO2 removes the need for its storage and containment. CO2 capture and utilization/re-use is defined in terms of conversion into value-added, lower-/zero-emission products, including fuels, chemicals, carbon fibers, biomass, and building materials. The CCU (carbon capture and utilization) should prove to be a useful tool in achieving zero/negative net emissions **[Zimmermann, A.W. et all, 2020].**

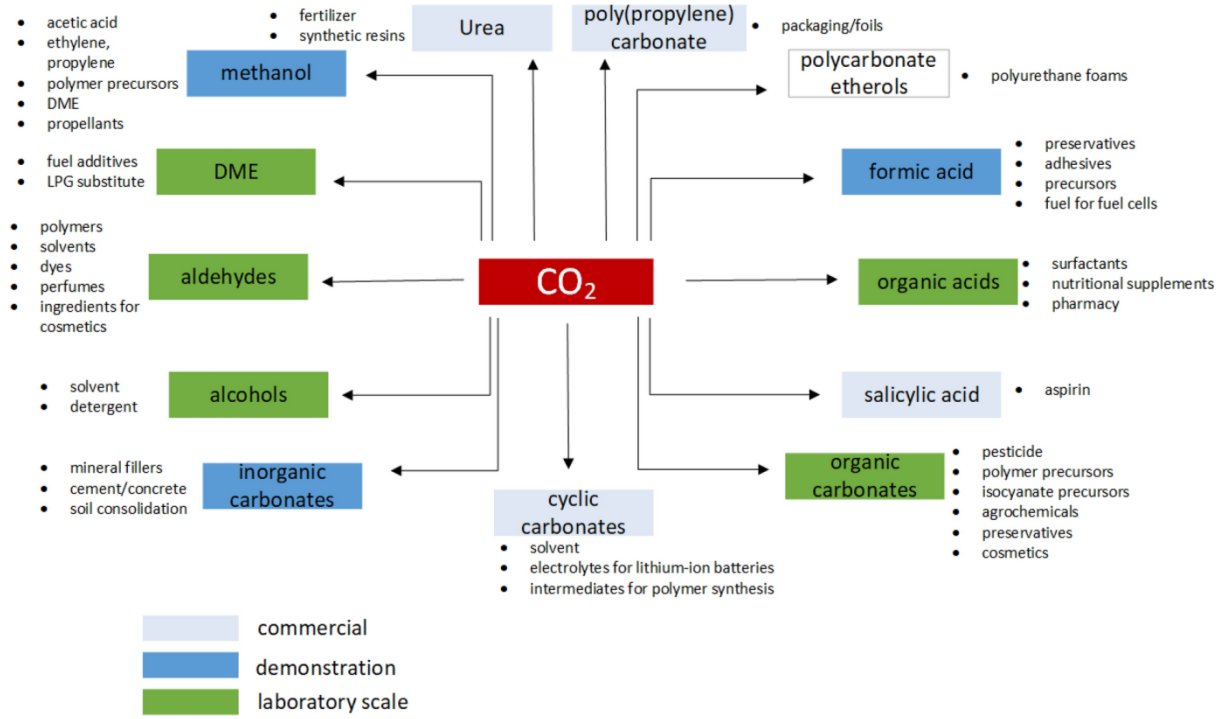
Microalgae-mediated CCU is a biotechnological process. In its first stage, CO2 is converted to biomass via photosynthesis [**In-na, P.; Byrne et all, 2022]**. The resultant biomass can be used to replace non-renewable fossil resources in the production of chemicals, fuels, bio plastics, diet supplements, cosmetics, pharmaceuticals, feedstuffs, and fertilizers.

Technologies for converting microalgae biomass to energy can be divided into two main groups: thermochemical and biochemical. The production of biofuels from microalgae includes dark fermentation with methane or hydrogen recovery [Wang, Y.; Yang at all, 2022], alcoholic fermentation to bioethanol, production of hydrogen from direct bio photolysis, production of biodiesel from storage lipids, pyrolysis gas [**Sekar, M.; Mathimani et all, 2021**] or syngas recovery in thermal processes, and energy recovery from direct combustion of microalgae biomass. In the energy transformation technologies of microalgae, apart from energy carriers, waste is generated, which is often used as fertilizer in agronomy [**Markou, G.; Monlau et all, 2019 https://doi.org/10.1016/B978-0-444-64192-2.00006-8**].

Microalgae can be used as a potential tool for long-term CO2 capture and utilization (Table 5)–for example, in the production of cement or bio plastics **[Naohiro Kato a, Tony Lum et all,2019**]. Production and utilization of bio carbon is another avenue of microalgae application–fixing carbon into soil provides long-term storage of CO2 and serves to promote sustainable agriculture. Microalgae can also potentially be used as bio stimulants to improve crop production, thereby reducing the need for chemical fertilizers. Micro algal biomass can also be used to produce bio plastics through CO2 bio sequestration. Bio plastics are environmentally-friendly materials, as they do not increase the CO2 pool and are quicker to biodegrade. Microalgae can contain high levels of polysaccharides, proteins or lipids, and may thus serve as an alternative to other bio plastics and replace traditional plastics and biodegradable materials (such as poly lactic acid and polyhydroxyalkanoates). Biodegradable bio plastics reduce the pollutant load on oceans and reduce landfill areas, currently overfilled with non-degradable plastics. Using microalgae for cement production can serve as another method of long-term CO2 capture. The process involves the precipitation of CaCO3 by certain photosynthetic microalgae or blue-green algae, as well as non-phototrophic bacteria

The application of CO2 capture with algae, also known as carbon capture and utilization (CCU) using microalgae, has several potential benefits and applications across various industries. Here are some key applications:

1. **Biofuel Production:** Microalgae can capture CO2 and convert it into biomass through photosynthesis. This biomass can then be processed to produce biofuels such as biodiesel, bioethanol, and bio hydrogen. These biofuels can serve as renewable alternatives to fossil fuels, reducing greenhouse gas emissions and dependency on non-renewable resources.
2. **Bio plastics:** CO2 captured by microalgae can be used to produce bio plastics. Microalgae biomass contains high levels of polysaccharides, proteins, and lipids, which can be converted into biodegradable plastics. Bio plastics produced from microalgae are environmentally friendly and can help reduce the pollution caused by traditional plastic.
3. **Nutraceuticals and Pharmaceuticals:** Microalgae biomass can be used to produce a wide range of nutraceuticals and pharmaceuticals. Algae-derived products such as omega-3 fatty acids, antioxidants, vitamins, and pigments have numerous health benefits and pharmaceutical applications.
4. **Carbon Sequestration:** Microalgae can be used to capture CO2 from industrial flue gases and other sources. The captured CO2 is converted into biomass, effectively sequestering carbon and reducing atmospheric CO2 levels. This process can help mitigate climate change by offsetting carbon emissions from industrial activities.
5. **Wastewater Treatment:** Algae-based systems can be used for CO2 capture and wastewater treatment simultaneously. Algae can utilize CO2 and nutrients from wastewater to grow, thereby reducing CO2 emissions and treating wastewater effectively. This approach provides a sustainable solution for both CO2 capture and wastewater treatment.
6. **Agricultural Applications**: Microalgae biomass can be used as a nutrient-rich fertilizer for agricultural crops. The biomass contains essential nutrients such as nitrogen, phosphorus, and potassium, which can improve soil fertility and crop yield. Additionally, microalgae-based fertilizers can help reduce the reliance on synthetic fertilizers, which can have harmful environmental impacts.
7. **Aquaculture Feed:** Algae biomass can be used as a sustainable feed source for aquaculture operations. Many species of fish and shellfish consume algae as part of their natural diet, making algae-based feeds an environmentally friendly alternative to traditional fishmeal and soy-based feeds.



TAKEN FROM – Application of CO_2 (**S.Kammerer, I.Borho et all, 2022)**

15. CONCLUSION

Electrochemical conversion of CO_2 to fuels and chemicals is a promising approach to reduce fossil fuel usage. With better catalysts, the process could solve energy storage problems for intermittent electricity sources such as wind and solar; it could also provide a source of carbon-based chemicals. Unfortunately, an ideal catalyst has not been found. This thesis will discuss insights into CO_2RR catalysis gained through studying the activity of Cu and a range of other metals using an experimental method with increased accuracy and sensitivity. Hopefully these and other insights will guide the development of improved catalysts. One of the major challenges in studying CO_2RR catalysts is difficulty in the experimental determination of catalyst activity. Using the experimental method outlined in this chapter, it is possible to accurately measure the activity of a CO_2RR catalyst. The major challenges that needed to be overcome were the generation and quantification of the products of the reaction and the accurate measurement of the potential where these products were formed. It is only with accurate methods to assess catalyst activity that it will be possible to get a better understanding of CO_2RR and begin to tackle the more fundamental problems of lowering the over potential and affecting the selectivity.

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