Alli, YA, Bamisaye, A, Bamidele, MO, Etafo, NO, Chkirida, S, Lawal, A, Hammed, VO, Akinfenwa, AS, Hanson, E, Nwakile, C, Kazeem, KO, Ayanwunmi, RJ, Ige, AS, Parga Torres, JR and Al Nageim, H

Transforming waste to wealth: Harnessing carbon dioxide for sustainable solutions

Results in Surfaces and Interfaces 17 (2024) 100321

Contents lists available at ScienceDirect

Results in Surfaces and Interfaces

journal homepage: www.elsevier.com/locate/rsurfi

Transforming waste to wealth: Harnessing carbon dioxide for sustainable solutions

Yakubu Adekunle Alli [a,*], Abayomi Bamisaye [b], Muyideen Olaitan Bamidele [c], Nelson Oshogwue Etafo [d], Soulaima Chkirida [e], Afolashade Lawal [f], Victor Oluwafolajimi Hammed [g], Ayobami Samuel Akinfenwa [h], Enobong Hanson [i], Chukwuebuka Nwakile [i], Kolawole Osuolale Kazeem [j], Rebecca Juliet Ayanwunmi [k], Akinsanmi S. Ige [l], Jose Refugio Parga Torres [d], Hassan Al Nageim [m,**]

[a] CNRS, LCC (Laboratoire de Chimie de Coordination), UPR8241, Université de Toulouse, UPS, INPT, Toulouse, cedex 4 F-31077, France
[b] Department of Chemistry, Faculty of Natural and Applied Sciences, Lead City University, Ibadan, Oyo State, Nigeria
[c] Department of Food Research, School of Chemistry, Universidada Autonoma de Coahuila, Ing. J. Cardenas Valdes S/N República 25280, Saltillo, Coahuila, Mexico
[d] Department of Metallurgy and Materials Science, Institute of Technology, Blvd. Venustiano Carranza 2400, Col. Tecnológico, C.P. 25280, Coahuila, Mexico
[e] Laboratory of Heterocyclic Organic Chemistry, Faculty of Sciences, University Mohammed V, Rabat, Morocco
[f] School for Environment and Sustainability, University of Michigan 440 Church St, Ann Arbor, MI 48109, USA
[g] Department of Nanotechnology, North Carolina A&T States University, Greensboro, NC, USA
[h] Mechanical Engineering, Georgia Southern University, 1332 Southern Drive Statesboro, GA 30458, USA
[i] Jones graduate school of business, Rice University, 6100 Main St, Houston, TX 77005, USA
[j] Department of Geotechnics, Roads and Geodesy, Faculty of Civil Engineering and Environmental Sciences, Bialystok University of Technology, 45A Wiejska Street, 15-351 Bialystok, Poland
[k] Department of Earth and Environmental science, Temple University, 1801 N Broad St, Philadelphia, PA, 19122, USA
[l] University of Arizona, 1200 E University Blvd, Tucson, AZ, 85721, USA
[m] School of Civil Engineering & Built Environment, Liverpool John Moores University, Liverpool, UK

ARTICLE INFO

Keywords:
CCU
sustainable solutions
CO_2 emissions
greenhouse gas

ABSTRACT

The escalating levels of carbon dioxide (CO_2) emissions present a critical challenge to global sustainability, considering that CO_2 is the primary cause of climate change. This dilemma presents a unique opportunity: converting waste CO_2 into useful resources. This review provides an in-depth analysis of CO_2 sources and waste streams, examining their potential as feedstocks for various industrial processes. By reviewing cutting-edge conversion technologies—such as catalysis, electrochemical, and photochemical methods—this work emphasizes how revolutionary ideas in Carbon Capture and Utilization (CCU) can play a pivotal role in reducing greenhouse gas emissions while generating both environmental and economic advantages. Through a systematic review of case studies and success stories in Carbon Capture and Utilization (CCU), the review illustrates the practical viability of these technologies. Additionally, the challenges facing CCU implementation, including economic, technical, and policy-related barriers, are explored. The review fills a critical gap by providing a comprehensive overview of both the current state and future potential of CO_2 utilization. Finally, it outlines future directions, emphasizing the need for interdisciplinary approaches, policy frameworks, and technological advancements to fully realize the potential of harnessing CO_2 for sustainable solutions.

1. Introduction

Carbon dioxide (CO_2) emissions, predominantly from the combustion of fossil fuels and industrial processes, have long been recognized as a significant contributor to global climate change. As a greenhouse gas, CO_2 traps heat in the atmosphere, leading to the

* Corresponding author.
** Corresponding author.
E-mail addresses: alliyakubu016@gmail.com (Y.A. Alli), H.K.Alnageim@ljmu.ac.uk (H. Al Nageim).

https://doi.org/10.1016/j.rsurfi.2024.100321
Received 23 August 2024; Received in revised form 26 September 2024; Accepted 9 October 2024
Available online 18 October 2024

phenomenon known as global warming (Amoo and Layi Fagbenle, 2020; Rafique, 2018). The concentration of CO_2 in the atmosphere has increased dramatically since the Industrial Revolution, reaching unprecedented levels and prompting widespread scientific and public concern (IPCC, 2021). The urgent need to address these emissions has catalyzed international agreements, such as the Paris Agreement, which aims to limit global temperature rise to well below 2 °C above pre-industrial levels (Saravanan et al., 2023a, 2023b).

The growing concerns about climate change and greenhouse gas emissions are not only environmental but also socio-economic. Climate change impacts are evident in the increasing frequency and severity of extreme weather events, sea-level rise, and disruptions to ecosystems and biodiversity (NASA, 2024.). These changes pose significant risks to agriculture, water resources, human health, and infrastructure, thereby affecting economic stability and social well-being. Consequently, mitigating CO_2 emissions is a critical global priority that requires innovative and sustainable solutions (Yaashikaa et al., 2023).

An emerging and transformative approach in environmental science is the concept of converting CO_2 from waste into valuable resources (Ferdoush et al., 2024). This strategy, commonly referred to as "carbon capture, utilization, and storage" (CCUS), aims to shift the perception of CO_2 from being merely an environmental burden to a significant economic resource. By capturing CO_2 emissions at their source and repurposing them into commercially valuable products, CCUS fosters the development of a circular carbon economy. In this model, CO_2 is continuously recycled rather than being released into the atmosphere, thus significantly mitigating its environmental impact. Beyond reducing the global carbon footprint, this approach unlocks new industrial applications and drives economic growth by creating markets for innovative products derived from CO_2. While numerous reviews have explored various aspects of CCUS (Davoodi et al., 2023; McLaughlin et al., 2023a), to our knowledge, there has not been a comprehensive review focused on the latest advancements in harnessing carbon dioxide for sustainable solutions. This gap highlights the need for a detailed analysis of recent progress in this rapidly evolving field.

This review seeks to fulfill a number of particular objectives. Prioritizing their effectiveness, scalability, and financial sustainability, it first aims to investigate and assess the most recent approaches to CO_2 capture, including chemical absorption, adsorption, membrane separation, and cryogenic techniques. Secondly, a comprehensive evaluation of the several paths for using collected CO_2 will be conducted in order to determine the possibility of converting CO_2 into high-value products such as chemicals, fuels, building materials, and polymers via catalytic, electrochemical, and biological processes. Third, the evaluation intends to give insights into the integration of renewable energy sources with these technologies, evaluating how such integration might improve industrial process sustainability and reduce total carbon footprint. Last but not least, the review intends to look at the technological, policy, and socioeconomic issues that prevent these technologies from being widely used and provide potential answers.

By examining real-world applications and case studies, this review aims to illustrate the practical viability and benefits of CO_2 conversion technologies. The review also seeks to address the socio-economic and policy dimensions required to support the widespread adoption of CCUS technologies, emphasizing the role of governmental incentives, international collaboration, and the potential for job creation and economic development. This review seeks to establish a robust justification for the ongoing and future research into CO_2 conversion technologies. By transforming CO_2 from waste to wealth, we can not only mitigate the adverse impacts of climate change but also drive innovation, create economic opportunities, and build a sustainable future. The insights provided in this review aim to inspire continued advancements in this field and inform policy and investment decisions that will shape the trajectory of global carbon management efforts.

In lieu of the above, the following research questions are the focus of this review: (1) Which are the most promising CO_2 capture and utilization technologies? (2) How can CO_2 be turned into value-added products to boost economic growth? (3) Where do CCUS technologies stand today and what are the main obstacles facing them in the future? By transforming CO_2 from waste to wealth, we can not only mitigate the adverse impacts of climate change but also drive innovation, create economic opportunities, and build a sustainable future. The insights provided in this review aim to inspire continued advancements in this field and inform policy and investment decisions that will shape the trajectory of global carbon management efforts.

2. Sources of CO_2 emissions and waste streams

CO_2 emissions stem from various anthropogenic activities and natural processes. Major sources include the combustion of fossil fuels for energy production, transportation, and industrial operations, which account for the largest share of global CO_2 emissions. Power plants, especially those using coal, oil, and natural gas, are significant contributors. Industrial processes, such as cement production, steel manufacturing, and chemical synthesis, also release substantial amounts of CO_2. In addition to direct emissions, CO_2 waste streams are generated as by-products in various industries. For instance, the fermentation process in breweries and distilleries produces CO_2, as does natural gas processing and refining. Other sources include wastewater treatment plants and agricultural practices, which emit CO_2 through the decomposition of organic matter. Understanding the diverse origins of CO_2 emissions and waste streams is crucial for developing targeted strategies for carbon capture, utilization, and storage, thereby reducing the overall carbon footprint and mitigating climate change impacts.

2.1. Industrial processes: power plants, cement production, steel manufacturing

2.1.1. Power plant

The global electricity access rate increased from 87% in 2015 to 91% in 2021, providing electricity to nearly 800 million more people. However, 675 million people still lacked access to electricity in 2021, mostly in least-developed countries (LDCs). Despite steady progress over the past six years, the annual growth rate of 0.6 percentage points between 2019 and 2021 is lower than the 0.8 percentage points seen from 2015 to 2019. In sub-Saharan Africa, due to population growth, the number of people without access has remained around 567 million since 2010 (UN, 2024). This therefore shows that that electricity consumption will continue to increase. The use of fossil fuels to generate electricity accounts for more than 40% of all energy-related CO_2 emissions. All power-producing technologies release greenhouse gasses at some point during their life cycle, which have enormous adverse effects on both humans and the ecosystem (WNA and Carbon Dioxide Emissions From Electricity, 2024).

The emissions that alter our natural environment are closely linked to coal combustion in the growing number of power plants. The CO2 emissions from these plants are driven by the need to meet the electricity demand of the growing population. Fig. 1 shows the carbon emissions from coal-fired plants in China. These emissions are also supported by industrialization and urbanization in which industrial growth and development take a chunk of the percentage. However, the CO2 emissions from energy generation have significant impacts on both the flora and fauna. The United Nations Framework Convention on Climate Change (UNFCCC) notes that these rising emissions contribute directly to increasing the global mean temperature by up to 2 °C annually (Nyirenda, 2023; Ali et al., 2021).

Energy projects under the China-Pakistan Economic Corridor (CPEC) are primarily fossil-fuel-based and use coal, which is a major contributor to greenhouse gases, particularly CO_2 emissions. Coal-fired power plants, reliant on coal combustion, pose environmental risks due to their potential to cause significant environmental degradation (Ali et al., 2021). They change atmospheric composition, enhance radiative

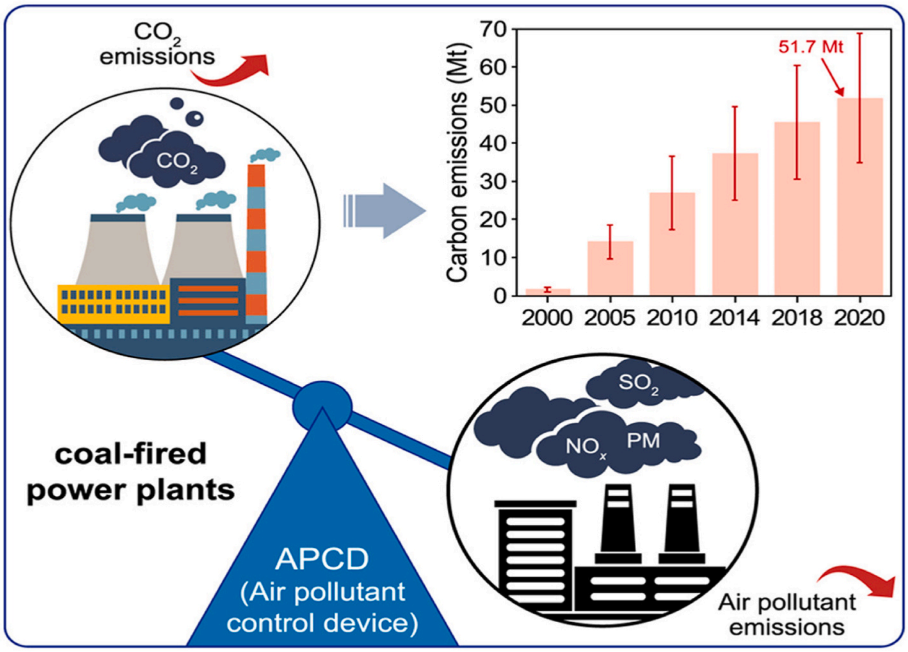

Fig. 1. Carbon emissions from coal-fired plant (Zhang et al., 2024).

forcing, contribute to global warming, and lead to glacier melting and sea level rise by approximately 7 meters (Ali et al., 2021; Irfan et al., 2024; Mariappan et al., 2022). Additionally, they cause air temperature increases by 5.5 °C, alter mountain cryospheres leading to glacier recession, glacial lake outburst floods (GLOFs), and create numerous glacier lakes (Ali et al., 2021; Irfan et al., 2024; Mariappan et al., 2022). These effects degrade agriculture, disrupt water systems and result in numerous irreversible environmental costs associated with coal-based power plants (Chataut et al., 2023).

2.1.2. Cement

Cement is the principal binding agent in concrete, which is used to build structures, infrastructure, and transportation systems worldwide, all of which substantially impact people's quality of life and socioeconomic status. Concrete is the world's second most consumed substance, after water (Pamu and Alugubelli, 2023; Kryeziu et al., 2023). Cement facilities emit considerable amounts of CO2, which come from a variety of processes. As shown in equation 1, the principal source is the calcination of limestone (CaCO3), which emits CO2 as it changes to lime (CaO) in kiln operations. The use of fossil fuels to heat kilns increases CO2 emissions. Furthermore, while alternative fuels used in cement production may reduce overall emissions, they still emit CO2. Other sources of CO2 emissions include electricity use, raw material and waste transportation, and plant auxiliary processes. Cement factories' waste streams often contain kiln dust, clinker cooler dust, and other particulates. These waste products frequently contain residual limestone, silica, and other minerals that can be reused or require specialist disposal. However, cement production is energy-intensive and strongly reliant on natural resources, which accounts for approximately 7% of total anthropogenic greenhouse gas (GHG) emissions in CO2 equivalents (Izumi et al., 2021). In 2018, the cement industry in Japan was the fourth-largest CO2 emitter, just after the power, steel, and chemical sectors (Izumi et al., 2021). About one-third of these emissions are owing to fuel burning, with the rest being due to process-related CO2 emissions from limestone decarbonization during the calcination process. This process is usually represented by the reaction in equation (1):

$$CaCO_3 + \text{heat} \Rightarrow CaO + CO_2\uparrow. \quad (1)$$

The summary of the source of CO2 in the environment is shown below as presented in Fig. 2, the number 1 in the chart below shows CO2 from raw materials such as limestone and carbonate, 2 shows CO2 sources from fossil fuels and alternative fuels used in the cement kiln, 3 depicts CO2 reacted by mineralization, and 4 shows CO2 from recarbonate.

2.1.3. Steel manufacturing

Steel is the world's highest energy consumption among industrial sectors. The mutual dependency of energy and the environment is widely understood. this therefore shows that steel manufacture is an energy-intensive process with substantial environmental impact (Conejo et al., 2020).

Steel production is predicted to grow by 25–30% by 2050. The dominant iron-making route, blast furnace (BF), especially, is an energy-intensive process based on fossil fuel consumption; the steel sector is thus responsible for about 7% of all anthropogenic CO_2 emissions as shown in Fig. 3 (Conejo et al., 2020; Yang et al., 2024a,b). To take up the 2050 challenge, emissions should see significant cuts. Steel manufacturing contributes significantly to CO2 emissions and waste streams. Primary sources include the use of fossil fuels to heat and reduce iron ore in blast furnaces, which generate CO2. Secondary sources come from the oxidation of carbon in coke used for iron ore reduction. Waste streams include slag, a byproduct of iron smelting, as well as particle and trace metal emissions (Yang et al., 2024a,b). Steelmaking also produces effluent that contains suspended particulates and dissolved metals, which must be treated. Addressing these difficulties requires adopting cleaner technology, such as electric arc furnaces fueled by renewable energy, and implementing efficient recycling to reduce environmental impact and resource use.

The blast furnace is the primary method for producing steel globally, with integrated plants producing about 70% of steel and the Electric Arc Furnace (EAF) producing 30% (71.5% and 28.0%, respectively, in 2017). The blast furnace uses coke and injected coal for energy and as a reducing agent, and producing one ton of coke requires 1.2–1.6 tons of coal (Conejo et al., 2020; Yang et al., 2024a,b). Preheating coal before coke-making reduces coal use and increases coke oven productivity. The blast furnace is a highly efficient thermal reactor, working with two countercurrent streams: descending solids and ascending gases, functioning as a heat exchanger. It produces its own reducing gas, CO

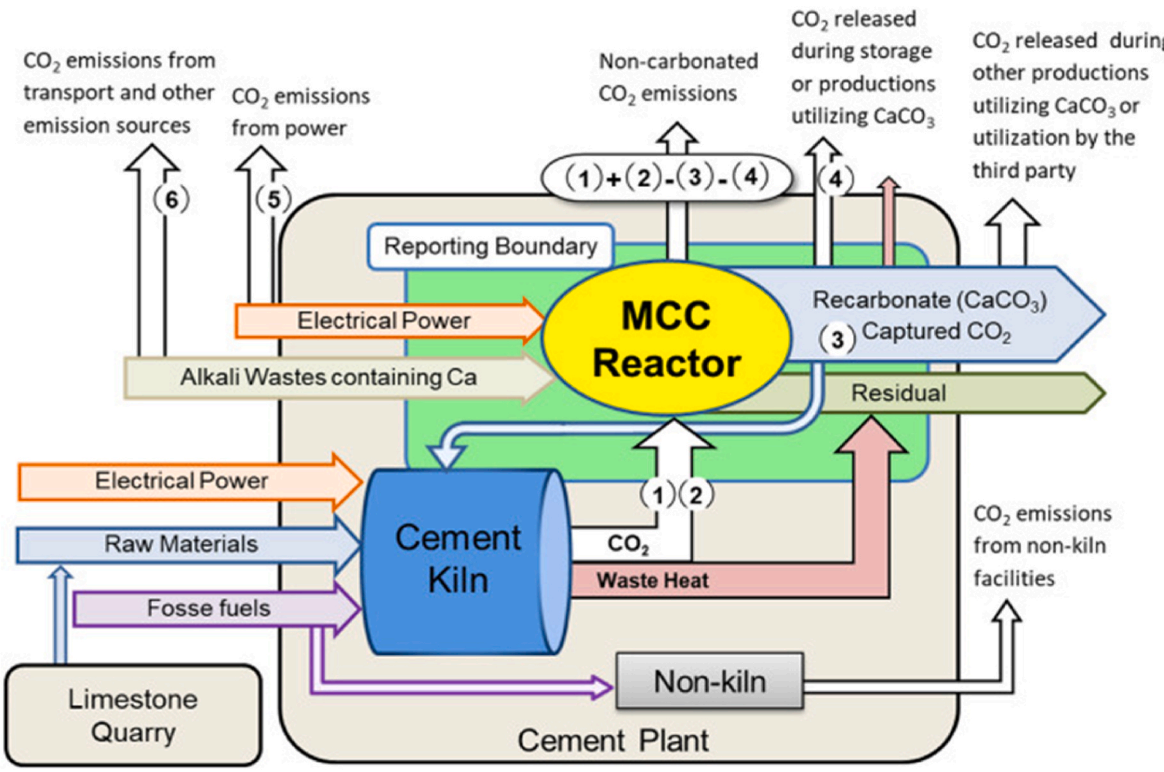

Fig. 2. Cement plant site, encompassing all input and output materials as well as CO2 streams (Izumi et al., 2021).

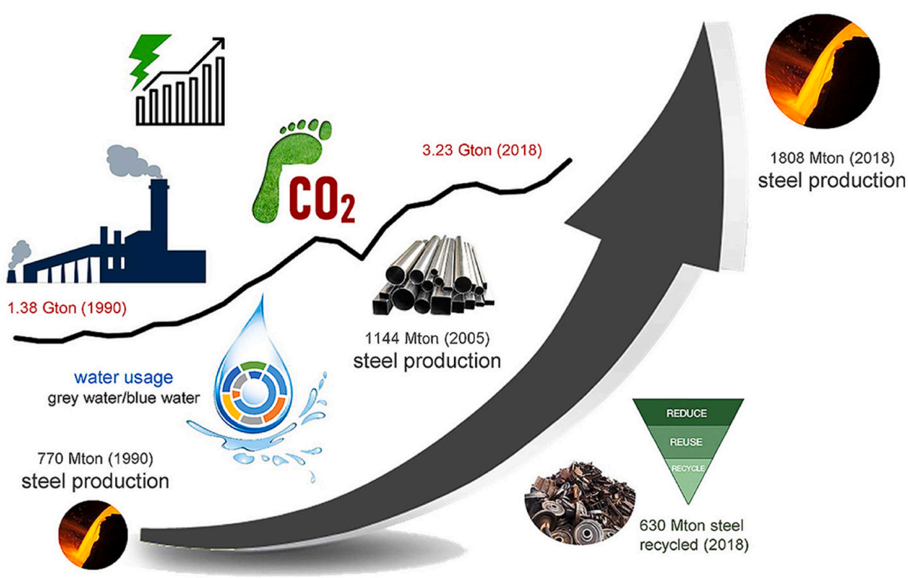

Fig. 3. Global steel production, energy consumption, and CO_2 emissions in the steel industry (Conejo et al., 2020).

(Conejo et al., 2020; Bailera, 2023). The reduction of iron oxide by CO generates CO_2 as shown in equation (2).

$$C_{(s)} + CO_{2(g)} = 2CO_{(g)}$$

$$Fe_3O_{4(s)} + 4CO_{(g)} = 3Fe_{(s)} + 4CO_{2(g)} \quad (2)$$

The blast furnace is a highly efficient thermal reactor that functions as a heat exchanger, using two countercurrent streams: descending solids and ascending gases (Yang et al., 2024a,b). It produces its reducing gas, CO, which is used to reduce iron oxide and generate CO_2.

2.2. *Transportation sector: cars, trucks, airplanes*

According to (Avogadro and Redondi, 2024) transport (including aviation) is the EU's largest source of GHG emissions (27%) and the only sector where current emissions exceed 1990 levels. Differences in transport patterns, as well as the use of alternative gas transport rate (k) models to estimate air-sea emissions, all contribute to increased uncertainty in GHG air-water flux estimates (Liu et al., 2022a). While cars account for the majority of transportation emissions (43.9%), heavy-duty transport has a combined impact of 46.2% (Gray et al., 2021). Greenhouse gas emissions have unanticipated consequences. The transportation industry accounts for approximately 20% of total CO2 emissions worldwide, with road traffic accounting for the majority (Azhar et al., 2024).

Furthermore, the global demand for transportation is expected to rise globally in the coming decades due to population growth, increased incomes, and more people affording cars, trains, and flights. According to the International Energy Agency (IEA, 2020) in its Energy Technology Perspectives Report as presented by (Ritchie, 2020) global transport demand (measured in passenger kilometers) is set to double. Car ownership rates are projected to increase by 60%, and demand for passenger and freight aviation is expected to triple by 2070. This will lead to a significant rise in transport emissions. Transport makes up about one-fifth of global carbon dioxide (CO2) emissions—24% if we only consider CO2 from energy sources (Ritchie, 2020)How are these emissions distributed among cars, trucks, planes, and trains? The chart in Fig. 4, from the IEA, shows that road travel was responsible for three-quarters of transport emissions in 2018. Of this, passenger vehicles (cars and buses) contributed 45.1%, and trucks accounted for 29.4%. Since road transport is 21% of total emissions and makes up three-quarters of transport emissions, it contributes 15% of global CO2 emissions. Aviation, often highlighted in climate discussions, accounts for 11.6% of transport emissions, emitting just under one billion tonnes of CO2 annually—around 2.5% of total global emissions. International shipping also contributes about 10.6%.

2.3. Agricultural activities: crop residues livestock farming

2.3.1. Livestock farming

Agriculture and related sectors, which form the backbone of many emerging and developing countries' economies directly or indirectly amount to about 82% of the world's population, must be sustainable to bring about greater human prosperity. This necessitates the introduction, use, and advancement of more effective industrial technology. Furthermore, atmospheric concentrations of greenhouse gases CO2, CH4, and N2O are increasing at rates of about 0.4, 0.6, and 0.25% each year, respectively (Flessa et al., 2002). The integrated assessment of greenhouse gas emissions as shown in Fig. 5a included those from fields, pasture, cattle, cattle waste management, fertilizer production, and consumption of fossil fuels, which could be cumulatively accrued to agricultural practice (Liu et al., 2022a; Li et al., 2024a). Increasing manure output poses a challenge for both livestock management and the global environment. Manure is commonly utilized as a fertilizer, but it can also enhance soil fertility and carbon sequestration through land application. However, using manure can increase emissions of poisonous gas. Furthermore, manure can increase soil carbon levels, but how it affects soil carbon varies based on local climate, soil type, and management practices (Qin et al., 2018). Better manure management is needed to balance crop productivity with climate change benefits (Smith et al., 2020). However, large amounts of manure can release significant nitrous oxide (N2O) and other gaseous pollutants a potent greenhouse gas with a warming effect 265 times greater than carbon dioxide (CO2) (Qin et al., 2018). Manure has been a major source of N2O since 1860 (Zhang et al., 2017) and was responsible for 44% of global N2O emissions in 2000 (Ramzan et al., 2020; Li et al., 2024b), Managing manure is a major challenge for climate change efforts (Zhang et al., 2017). Recent studies show that applying manure to fields can increase N2O emissions by 130% compared to using mineral fertilizers alone, potentially reducing the climate benefits of soil carbon storage by 36.7%. Besides on-farm emissions, off-farm activities like fertilizer production and manure transport also contribute to greenhouse gas emissions, a complete assessment of manure and mineral fertilizers must include both on-site and off-site emissions to understand manure's full impact on climate change (Ghosh et al., 2020; Escribano et al., 2022).

2.3.2. Crop residue

Managing the increasing amounts of biomass and other solid wastes poses a significant challenge in both industrialized and developing countries (Oladoye et al., 2024; Bamisaye et al., 2024). Proper collection, recycling, and disposal of these materials are critical. Converting them into energy or other products can help minimize the impact on the environment while also creating valuable resources, particularly in underdeveloped nations where biomass is abundant (Saravanan et al., 2023a, 2023b; Yaashikaa et al., 2023; Kumar et al., 2023a). The principal application of biomass waste has been for energy generation via the direct combustion of wood and crop residue (Oladoye et al., 2024; Hills et al., 2020; Bamisaye and Rapheal, 2023). In many underdeveloped nations, biomass is primarily utilized to fuel open fires for cooking and heating (Malico et al., 2024). Nearly three billion people worldwide

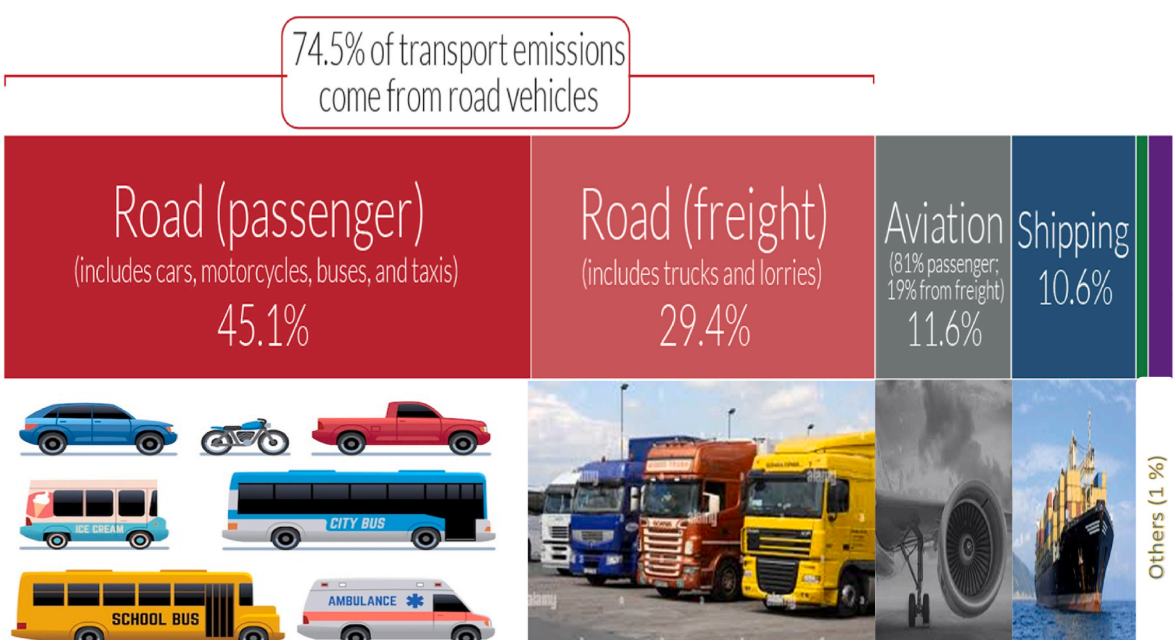

Fig. 4. The source of carbon dioxide (CO_2) emissions in the transportation industry.

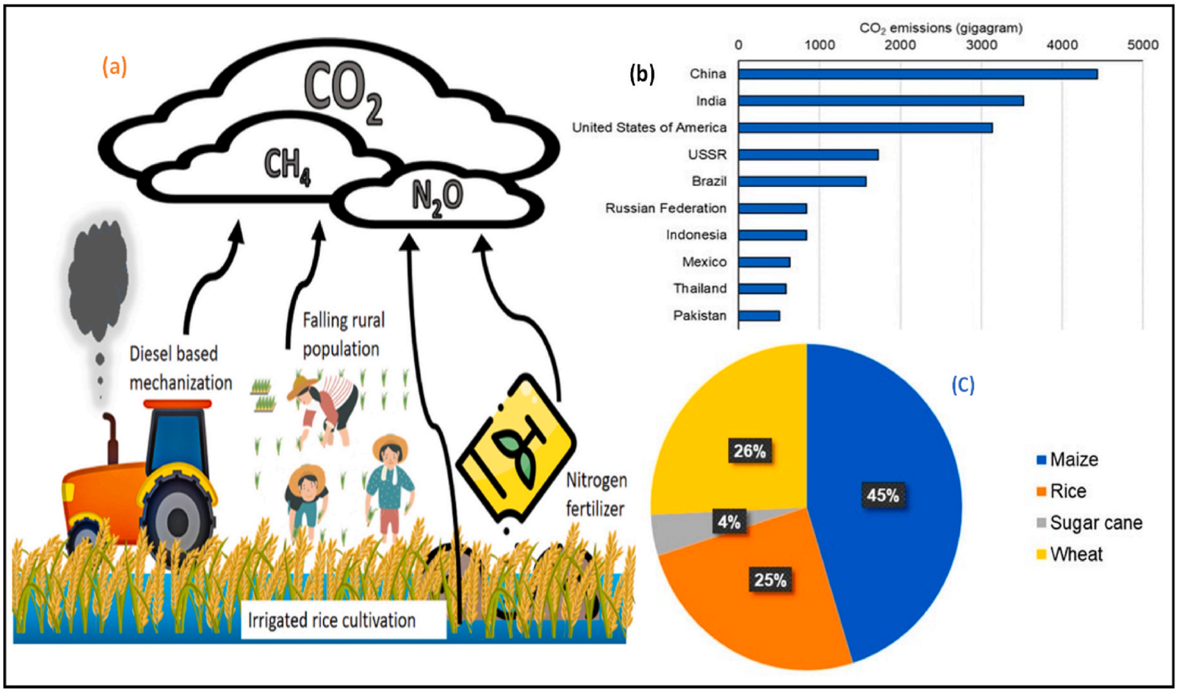

Fig. 5. agricultural practice as a Source of CO2 emission (Aziz and Chowdhury, 2023) (b) CO2 Emissions (in gigagram unit) from the burning of crop residues and (c) Major CO_2 emitting countries (in gigagram unit) based on burning of crop residues (Sarkar et al., 2020).

use biomass fuels for cooking and heating, such as wood, briquette, or charcoal (Das et al., 2024; Bamisaye et al., 2023; Bamisaye and Rapheal, 2021). This shows that crop residues play a dual role in agriculture, they provide useful organic matter while also potentially contributing to CO2 emissions and waste (Ahmad et al., 2024). When not properly managed, leftovers such as stalks and husks break down anaerobically, emitting methane, a potent greenhouse gas. Improper disposal also causes soil nutrient loss and runoff, which affects water quality (Piccoli et al., 2024; Kumar et al., 2023b). However, these wastes can be converted into biofuel or composted as compost, lowering emissions and improving soil health. Sustainable management strategies are critical for reducing environmental consequences while increasing agricultural sustainability. Intensive farming often exacerbates soil and water erosion, making the land more vulnerable to damage and resulting in the loss of precious natural resources (Sarkar et al., 2020). Burning crop leftovers on-site emit methane (CH4) and nitrous oxide (N2O), which contribute to greenhouse gas emissions. Maize is the crop with the highest residue-burning emissions (in CO2 equivalent—gigagrams), followed by rice, wheat, and sugarcane (Fig. 5c). China, India, the United States, and the Soviet Union are the leading sources of greenhouse gas emissions (CO2 equivalent—gigagrams) from crop residue combustion (Fig. 5b). Poor management of crop leftovers, particularly burning them on site, poses considerable environmental risk. This practice affects both human health and the environment. Studies have shown that in most Asian countries, crop residues account for more than one-third of total biomass combustion (Huang et al., 2024). The discharge of particles such as PM10 and PM2.5, as well as greenhouse gases, contribute significantly to environmental pollution (Sarkar et al., 2020).

2.4. Municipal waste: landfills, waste-to-energy facilities

Municipal waste, which includes both residential and commercial refuse, is a substantial source of CO2 emissions and waste streams. Landfills, the principal disposal sites for urban waste, contribute to greenhouse gas emissions via the anaerobic decomposition of organic matter, which produces methane—a greenhouse gas substantially more potent than CO2 (Kiehbadroudinezhad et al., 2024; Abdel-Shafy et al., 2024). While municipal waste incineration lowers volume, it emits CO2 and other pollutants, contributing to air pollution and climate change (Choi and Rhee, 2024). Municipal waste that is not adequately managed can produce leachate, which contaminates soil and water sources.

Landfilling is a prominent and cost-effective form of disposal of waste in several African countries (Idowu et al., 2019). In landfills, microorganisms degrade waste in the absence of oxygen, resulting in leachate and landfill gas (LFG) (Choi and Rhee, 2024; Barros et al., 2018). The rate of decomposition is determined by temperature, moisture, waste content, and waste age (Lou et al., 2024; Mbazima et al., 2022). LFG is composed of up of 50–60% methane (CH_4), 40–50% carbon dioxide (CO2), 2–5% nitrogen, less than 1% ammonia, and trace amounts of oxygen, non-methane organic compounds (such as acrylonitrile and benzene), sulfides, hydrogen, and carbon monoxide (Mbazima et al., 2022). In 2016, the global municipal solid waste (MSW) was approximately 2.01 billion tons, with forecasts of 3.4 billion tons by 2050. Economic expansion, population growth, and urbanization are all predicted to contribute to increased waste generation. Unfortunately, at least 33% of this trash is disposed of openly and not in an environmentally acceptable manner (Mbazima et al., 2022).

Recycling and composting schemes can help to alleviate some of these effects, although inconsistent participation and contamination of recyclable materials remain issues. Furthermore, waste transportation and processing take a lot of energy, contributing to emissions.

2.5. Identifying key sources and volumes of CO_2 emissions and waste streams suitable for conversion

Understanding and identifying significant sources and volumes of CO_2 emissions is critical to effective climate change mitigation. CO2 emissions are caused by energy production, transportation, industry, and agriculture. Energy generation, primarily from fossil fuels, is the major contributor, followed by transportation emissions from vehicles, ships, and planes. Industrial processes, particularly cement and steel production, make a considerable contribution as well. Agricultural practices, such as deforestation and soil management, play a crucial role. Addressing these challenges necessitates a comprehensive approach that involves waste reduction at the source, effective recycling systems, and advances in waste-to-energy technologies. The transitioning to renewable energy, increasing energy efficiency, supporting sustainable transportation, and improving agricultural practices will be possible by precisely estimating emissions from these various sectors of the global economy as shown in Table 1, Which is a comprehensive approach, critical to effectively reducing global carbon emissions and combating climate change. More so, Identifying key sources and volumes of CO_2 emissions and waste streams suitable for conversion is essential for effective environmental management and sustainability. This will enable researchers and policymakers to develop and implement specific initiatives to mitigate global CO2 emissions.

3. Conversion technologies and processes

CO_2 has become a new frontier in environmental research and industrial innovation in its use as a sustainable resource (Sadiq et al., 2024). With increasing concerns about greenhouse gas emissions and their effects on climate change, a trend is shifting toward the conversion of CO_2 from waste entities into useful resources (Bhattacharjee et al., 2023). From this perspective, the application of various types of technologies for conversion and collection further transforming CO_2 into products that can be utilized. These processes include carbon capture, chemical conversion, biological and enzymatic processes, and electrochemical conversions (Fig. 6). The conversion of CO_2 into treasures is crucial for environmental sustainability and resource efficiency (Arun et al., 2024). Carbon capture and utilization (CCU) technologies, biological use of CO_2, mineralization, and carbonation are among the most appropriate techniques for capturing CO_2 (Mahmoudi Kouhi et al., 2024; Ho and Iizuka, 2024). The concepts presented align with the principles of the circular economy, which seeks to transform waste into valuable resources while minimizing environmental impacts.

Table 1
Key sources and volumes of CO2 emissions and waste streams suitable for conversion.

Categories	Sources	Volumes	Conversion Potential
Agricultural and Forestry wastes	Crop residues, animal manure, soil management, enteric fermentation in livestock, rice production, Logging residues, sawmill waste, deforestation, land use changes, synthetic fertilizers.	Large, seasonally variable volumes; global crop residue production is estimated at billions of tons annually. Substantial, especially in timber-producing regions Around 10% of global greenhouse gas emissions, with a significant portion as CO_2 from deforestation and soil management	Biofuels, biogas, biochar. Bioenergy, wood pellets and briquette
Industry, residential and commercial buildings	Household waste, commercial waste, manufacturing processes, and chemical production. Heating, cooling, and electricity usage in homes and commercial buildings Space heating, air conditioning, lighting, appliances	Varies by industry; significant quantities in heavy industries like steel and cement	Waste-to-energy (WTE) incineration, anaerobic digestion for biogas, and recycling.
Energy production	Fossil fuel combustion for electricity and heat (coal, natural gas, oil).	Accounts for approximately 42% of global CO2 emissions	Power plants, industrial boilers,
Transportation	Combustion of gasoline and diesel in cars, trucks, airplanes, ships, and trains	Responsible for approximately one-third of global CO2 emissions.	Road transport, aviation, shipping

3.1. *Carbon capture and utilization (CCU) technologies*

Carbon capture and utilization (CCU) technologies are crucial for mitigating climate change and transitioning to sustainable energy systems. These technologies focus on capturing carbon dioxide emissions and converting them into valuable products, addressing environmental concerns while creating economic opportunities (Mohammed et al., 2024). Direct Air Capture (DAC) and industrial capture systems are promising CCU technologies. CCU technologies aim to mitigate the adverse effects of CO_2 emissions, which are primary drivers of climate change. By capturing CO_2 and repurposing it, CCU not only reduces atmospheric CO_2 levels but also offers a sustainable supply of carbon for various industrial processes Fig. 7. This approach aligns with the principles of a circular economy, where waste is minimized, and resources are continually reused (Roy et al., 2023; Maselli et al., 2024; McLaughlin et al., 2023b).

3.1.1. *Direct air capture*

Direct Air Capture (DAC) is a technology that captures CO_2 directly from the atmosphere, thereby addressing the widespread nature of atmospheric CO_2. DAC systems can be classified into two categories: liquid solvents and solid sorbent systems (Chowdhury et al., 2023; Ayeleru et al., 2023).

- **Liquid Solvent Systems**: Ambient air passes through a chemical solvent such as an amine-based compound, which reacts with CO_2 to form a stable compound. The CO_2 -laden solution was heated to release the concentrated CO_2 and to regenerate the solvent for reuse (Gautam and Mondal, 2023).
- **Solid Sorbent Systems**: These Solid materials, such as Metal-Organic Frameworks (MOFs) or zeolites, with high CO_2 affinities. Air passes over these sorbents, and CO_2 was absorbed on their surfaces. The sorbents were then heated or vacuumed to release the concentrated CO_2 (Boer et al., 2023; Dziejarski et al., 2023a).

Direct Air Capture (DAC) offers a sustainable solution for reducing atmospheric CO_2 levels by converting it into carbon-neutral fuels, such as methanol or synthetic gasoline, using renewable energy (Goren et al., 2024). CO_2 can also be used for chemical production, reducing reliance on fossil fuels, and sequestered in underground formations, such as depleted oil and gas reservoirs or deep saline aquifers (Wu et al., 2025). reported that a 2D single-atom solution captures carbon dioxide from air at ambient temperature using mechanical effects instead of thermal, electrochemical, or chemical processes. This method, using a specially designed compressor, reduces energy consumption to 0.56 GJ/t, significantly lower than traditional systems, potentially revolutionizing air carbon capture (Monteagudo et al., 2024). found that biochar derived from olive pomace, activated with KOH, showed higher surface areas and micropore volumes, doubling its CO_2 adsorption capacity to 40 mg/g. The adsorption process was both chemical and physical, enhancing biochar/KOH adsorption rates (Surkatti et al., 2025). studied functionalized mesoporous silica (SBA-15) for DAC under dry and humid conditions, finding that various amines improved CO_2 adsorption and capacity, though there was a trade-off in thermodynamic efficiency due to water desorption energy. Stability tests showed robust regenerability over 10 cycles (Deka et al., 2025). demonstrated the efficacy of TiO_2 in

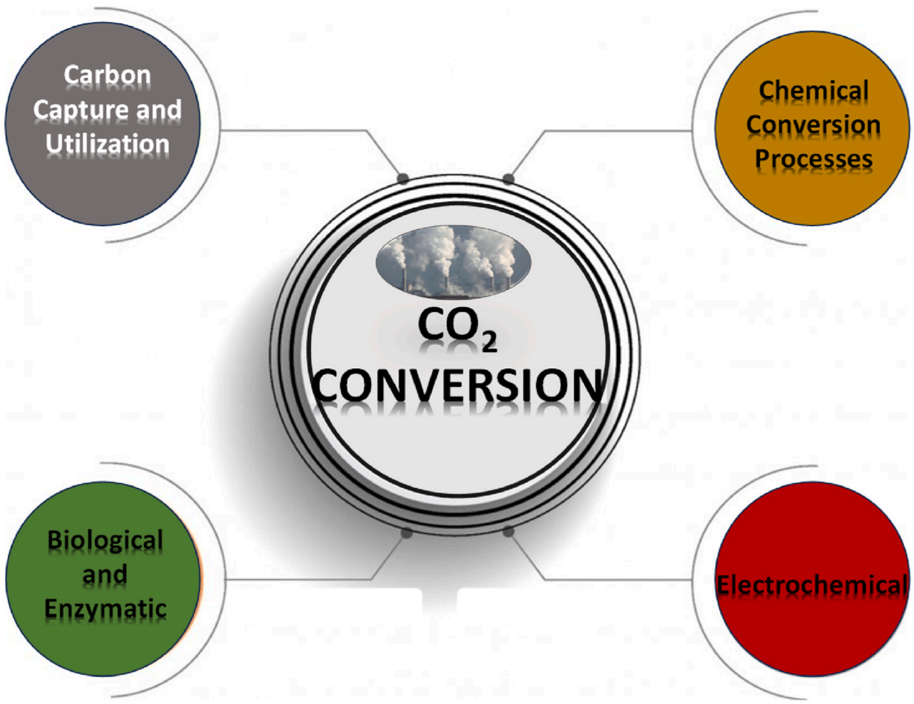

Fig. 6. CO_2 Conversion processes.

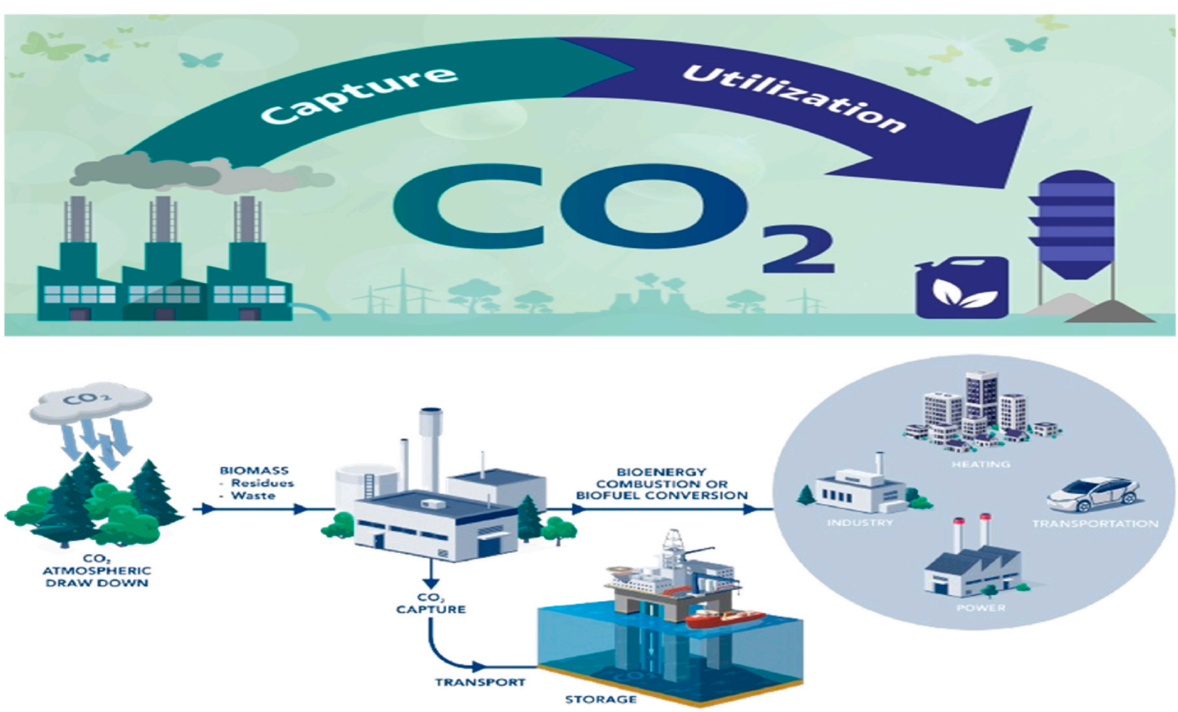

Fig. 7. Carbon capture and utilization (CCU) technologies.

regenerating potassium sarcosinate solvent using CO_2, significantly increasing the desorption rate and cumulative CO_2 removal at 95 °C, reducing total regeneration energy by approximately 50%, thus improving the commercial viability of absorption-based CO_2 capture systems.

3.1.2. Industrial capture systems

Industrial capture systems are designed to capture CO_2 emissions from sources, such as power plants, cement factories, and steel mills, before they are released into the atmosphere (Perpiñá et al., 2023). These systems use various techniques.

i. **Post-combustion capture**: Post-combustion capture (PCC) systems are used to capture CO2 from the flue gas emitted after fuel combustion in industrial processes and power plants (Su et al., 2023). These systems use physical or chemical processes such as absorption, adsorption, and membrane separation to enrich CO_2 from flue gas. Advanced materials such as metal-organic frameworks, zeolites, and novel solvents improve CO_2 capture efficiency and selectivity (Xu et al., 2023). PCC systems can be integrated into existing infrastructure, making them a cost-effective solution for reducing carbon emissions (Quang et al., 2023). They are used in power generation, cement production, and steel manufacturing.

ii. **Pre-combustion capture**: Pre-combustion capture involves the gasification of fossil fuels to produce a synthesis gas (syngas) with hydrogen and carbon monoxide (Alsunousi and Kayabasi, 2024). This gas undergoes a water-gas shift reaction, converting carbon monoxide into CO_2 and hydrogen. CO_2 is separated and captured, whereas hydrogen is used as a clean fuel. This method is particularly beneficial for integrated gasification combined cycle power plants, producing "blue hydrogen," which is a low-carbon energy source (Choi et al., 2024).

iii. **Oxy-fuel combustion**: Oxy-fuel combustion, a process in which fossil fuels are burned in pure oxygen, results in the production of flue gas primarily composed of carbon dioxide and water vapor, which can be easily separated and captured (Bazooyar and Jomekian, 2024; Cheng et al., 2024). This method is efficient and cost-effective, offering higher combustion temperatures and reduced nitrogen oxide emissions. It is also suitable for retrofitting existing power plants and can be integrated into new infrastructure. In addition, oxy-fuel combustion is beneficial for capturing CO_2 from biomass power plants, leading to carbon-neutral or carbon-negative energy production when combined with CO_2 storage (Tan et al., 2023).

Industrial capture systems have applications in the following areas.

i. **Enhanced Oil Recovery (EOR):** Industrial capture systems are crucial for EOR, as they provide CO_2 to boost oil extraction from reservoirs. The process includes capturing CO_2 from sources such as power plants and cement factories or using advanced technologies to capture it directly from the air (Olabi et al., 2022). The captured CO_2 is then compressed, transported via pipelines to oil fields, and injected into the depleting reservoirs. This injection reduced the oil viscosity and increased the reservoir pressure, facilitating easier extraction (Davoodi et al., 2024). CO_2-EOR not only improves oil recovery but also provides underground storage of CO2, thereby alleviating the impact of climate change and reducing greenhouse gas emissions (Dutta et al., 2024). Combining EOR with Carbon Capture and Storage (CCS) offers mature technology that sequesters CO_2 and improves oil production (Zhou et al., 2024). Advanced technologies such as direct air capture (DAC) provide a sustainable CO_2 source, supporting negative carbon emissions when integrated with storage (Ottenbros et al., 2024a).

ii. **Chemical manufacturing**: Industrial capture systems in chemical manufacturing aim to capture and manage CO_2 and other emissions to improve process efficiency and environmental sustainability. These systems are used in various industrial processes such as polymer processing and synthetic fuel production. They also manage hazardous dust, improve workplace safety, and reduce environmental impact. Advanced monitoring systems track the emissions of gases such as nitric oxide and nitrogen dioxide, ensuring compliance with environmental regulations. CO_2 capture from chemical manufacturing contributes to carbon capture and storage initiatives, reducing greenhouse gas emissions and supporting climate change mitigation efforts (Gabrielli et al., 2020; Raganati and Ammendola, 2024).

iii. **Construction Materials**: Industrial capture systems are used in the construction materials industry to manage and utilize CO_2 to enhance sustainability and efficiency. The applications include the injection of CO_2 into materials, such as concrete, to improve properties and reduce carbon footprints. Reality Capture technologies, such as 3D laser scanning and photogrammetry, create accurate digital models of construction sites and structures and enhance project efficiency and safety. Modular and containerized carbon capture systems make CO_2 capture more efficient and adaptable to various industrial applications, including construction, making them suitable for scalability and easy integration into existing processes (Hu and Assaad, 2024; Qureshi et al., 2024).

(Lu et al., 2024) developed an energy-efficient CO_2 absorbent using molecular dynamics simulations, combining N, N-dimethylethanolamine (DMEA) with ethylene glycol (EG) and various activators such as ethanolamine (MEA), ethylenediamine (EDA), and piperazine (PZ). Among these, DMEA-PZ-EG exhibited the highest CO_2 absorption rate and capacity, achieving 6.35 g- CO_2/(kg-soln.min.) and 96.5 g-CO2/kg-soln, respectively, reflecting improvements of 230.1% and 206.35% over the 2M DMEA-EG absorbent. Furthermore, DMEA-based absorbents reduced energy consumption by 33.93–51.56% compared to a 30 wt% MEA solution (Yang et al., 2024a,b). introduced a method for synthesizing cost-effective mesoporous solid amine adsorbents from industrial waste silica fume and tetraethylenepentamine. The optimized MPS-TEPA-30 sample demonstrated excellent CO2 adsorption capacity and stability with effective performance at low pressures, indicating its potential for ambient CO2 capture. Its thermal stability and predicted adsorption selectivity further enhance its suitability for high-temperature processes.

3.1.3. Synergies and innovations in CCU technologies

The incorporation of Direct Air Capture (DAC) and industrial capture systems enhances the effectiveness of Carbon Capture and Utilization (CCU) technologies. Advances in materials science, process engineering, and renewable energy integration have driven these improvements. Cutting-edge materials such as metal-organic frameworks (MOFs), zeolites, and novel solvents enhance the efficiency and selectivity of CO_2 capture (Obi et al., 2024; Mabuchi et al., 2024). Intensification process aims to create compact and high-efficiency capture systems that are seamlessly integrated into industrial processes (Raganati and Ammendola, 2024). Renewable energy sources, such as solar, wind, and geothermal power, can power DAC systems, regenerate solvents, and compress captured CO_2, thereby reducing the carbon footprint (Ozkan, 2024a). Advanced catalysts, including metal-based and composite catalysts, have significantly improved CO_2 conversion efficiency. Utilizing the waste heat from industrial processes further enhances the energy efficiency of CO_2 capture and conversion technologies (Wang et al., 2024a). Process optimization and real-time monitoring are crucial for improving the performance and yield of CO_2 conversion technologies (Samad et al., 2024). Advances in molecular dynamic simulations have led to the development of novel CO_2 absorbents that significantly enhance absorption performance and reduce energy consumption (Chen et al., 2024). Hybrid materials, such as mesoporous solid amine adsorbents synthesized from industrial waste, provide a cost-effective and efficient CO_2 capture solution, demonstrating superior adsorption capacities and stability (Yang et al., 2024a,b). Synergies and innovations in CO_2 conversion technologies are driving the field toward more sustainable and economically viable solutions for CO_2 reduction and utilization.

3.2. Chemical conversion processes

Chemical conversion processes are essential for transforming CO_2 into valuable environmentally beneficial products. These processes help mitigate global warming and provide a sustainable carbon source for various industries, aligning with circular economy principles by promoting resource efficiency and minimizing waste. Typically, these processes use catalysts to convert CO_2 into fuels, chemicals, and materials, thereby enhancing economic and environmental outcomes (Gupta et al., 2024).

3.2.1. CO_2 conversion to fuels

CO_2 can be converted into fuels to provide a sustainable alternative to fossil fuels and to reduce the carbon footprint of the energy sector. Methanol (**equation (3)**), a versatile fuel and chemical feedstock, can be synthesized from CO_2 through catalytic hydrogenation, in which CO_2 reacts with hydrogen over a copper-based catalyst at high temperatures and pressures. Methanol can be used in internal combustion engines as a feedstock for producing chemicals such as formaldehyde and acetic acid and in fuel cells for electricity generation. Synthetic Natural Gas (SNG) can be produced by converting CO_2 into methane (**equation (4)**), which is a substitute for natural gas in heating, electricity generation, and transportation. Fischer-Tropsch synthesis can convert a mixture of CO_2 and H_2 into liquid hydrocarbons (**equation (5)**), such as diesel and jet fuel, compatible with existing fuel infrastructure and engines, providing a seamless transition from fossil fuels.

$$CO_2 + 3H_2 \rightarrow CH_3\,OH + H_2\,O \qquad 3$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2\,O \qquad 4$$

$$(2n+1)H_2 + nCO_2 \rightarrow C_n\,H2_n+2 + nH_2\,O \qquad 5$$

3.2.2. CO_2 conversion to chemicals

CO_2 can be utilized as a feedstock for the synthesis of various chemicals, thereby reducing reliance on fossil-based carbon sources. Formic acid is a chemical with significant value in agricultural, textile processing, and preservative applications. Formic acid can be produced through the electrochemical reduction of CO_2 (Patil et al., 2024). Urea, which is extensively applied in fertilization and chemical manufacturing, can be generated through the Bosch-Meiser urea process by combining CO_2 and ammonia (NH_3). Polycarbonates are durable plastics that are used in construction, electronics, and medical devices. They can be synthesized by polymerizing CO_2 with epoxides using a metal complex catalyst.

3.2.3. CO_2 conversion to materials

Carbonate conversion into materials presents the dual benefits of carbon sequestration and innovation. The process of carbonate mineralization involves the reaction of CO_2 with metal oxides, resulting in the formation of stable carbonates, which are subsequently employed in the production of construction materials such as concrete and aggregates. Concrete curing enhances the strength and durability of concrete while sequestering CO_2. The conversion of CO_2 into graphene, a material with remarkable mechanical, electrical, and thermal properties, is a promising solution for addressing global warming and promoting sustainability. Graphene production provides a means of converting CO_2 into fuels, chemicals, and materials, thereby supporting a circular economy and reducing greenhouse gas emissions. These chemical conversion processes have a significant potential for mitigating climate change and contributing to a more sustainable future.

3.3. Biological and enzymatic conversion

Biological and enzymatic conversion processes offer innovative pathways for transforming carbon dioxide (CO_2) and other feedstocks into valuable products. Microbial fermentation and algal cultivation are two prominent techniques that leverage the natural capabilities of microorganisms and algae to convert CO_2 into fuel, chemicals, and materials. These processes offer several advantages, including mild operating conditions, high specificity, and the ability to use renewable feedstock. By harnessing the power of nature, these techniques can provide sustainable alternatives to traditional chemical processes (Karishma et al., 2024; Sahu et al., 2024).

3.3.1. Microbial fermentation

Microbial fermentation is a metabolic process that converts substrates, such as sugars and CO_2 into desired products, enabling the production of various biofuels, chemicals, and materials. This process produces biofuels, chemicals, and materials in a series of steps including substrate uptake, metabolic conversion, and product formation (Ray et al., 2024).

i.**Substrate Uptake**: Microorganisms take up substrates such as glucose or CO_2, from their environment.
ii.**Metabolic Conversion**: Enzymes within microorganisms catalyze reactions that convert substrates into intermediate metabolites.
iii.**Product Formation**: These metabolites are further transformed into final products that can be secreted by cells.

Microorganisms and metabolic pathways can be optimized to produce specific products through engineering or selection.

Microbial fermentation is a versatile process that is used to produce biofuels, chemicals, and materials (Ogundele et al., 2024).

•**Biofuel Production**

Microbial fermentation can generate various biofuels such as bioethanol, biobutanol, and biodiesel from renewable feedstocks.

i.**Bioethanol**: Saccharomyces cerevisiae yeast can convert sugars from biomass like corn and sugarcane into bioethanol, which can be blended with gasoline or used as a standalone fuel.
ii.**Biobutanol**: Clostridium species can produce butanol, a high-energy-density biofuel with superior blending properties compared to ethanol, through the fermentation of sugars.
iii.**Biodiesel**: Microorganisms like microalgae and engineered yeast can produce lipids that can be trans esterified to create biodiesel.
•**Chemical Production**: Microbial fermentation produces various chemicals that are utilized in various sectors, such as industry, agriculture, and pharmaceuticals.
i.**Lactic Acid**: Lactic acid bacteria convert carbohydrates into lactic acid, which is used in food preservation, biodegradable plastics, and pharmaceuticals.
ii.**Succinic Acid**: Engineered Escherichia coli can produce succinic acid, a precursor for polymers, solvents, and pharmaceuticals, from CO_2 and glucose.
iii.**Acetone-Butanol-Ethanol (ABE)**: Clostridium species can generate a mixture of acetone, butanol, and ethanol via fermentation.
•**Material Production**: Microbial fermentation can produce biopolymers and other materials with various applications in packaging, agriculture, and medicine.
i.**Polyhydroxyalkanoates (PHAs)**: Bacteria such as Cupriavidus necator can produce PHAs, which are biodegradable polymers used in packaging and medical devices, from various carbon sources.
ii.**Cellulose and Hemicellulose**: Engineered microorganisms can produce cellulose and hemicellulose, which are used in the production of bio-based materials and composites.

3.3.2. Algal cultivation

Algal cultivation converts CO_2 and nutrients into biomass, which is suitable for sustainable bioconversion due to their efficient photosynthesis, making them ideal candidates for fuel, chemical, and material production Figure 8 (Carmona-Martínez and Jarauta-Córdoba, 2024a). Algal cultivation utilizes the natural photosynthetic abilities to convert CO_2 and water into organic compounds and oxygen through various mechanisms.

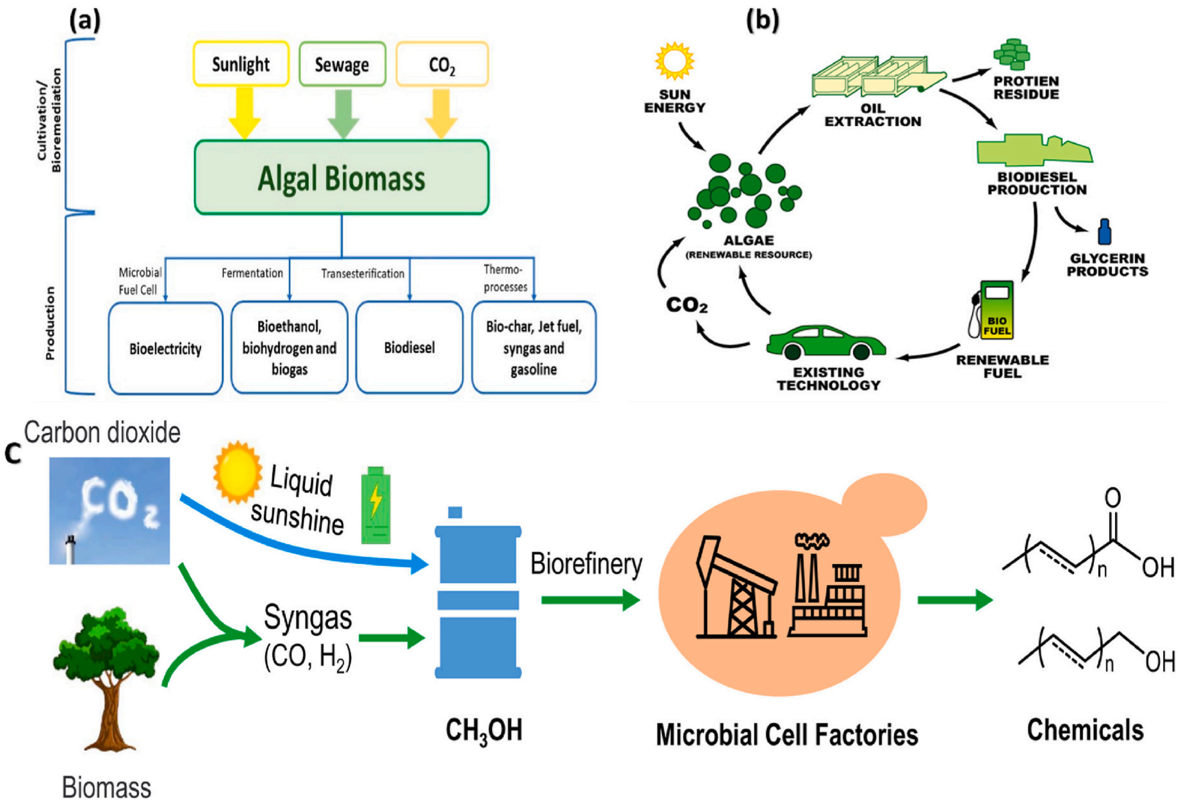

Fig. 8. (a) Algal conversion from CO2 to fuel, chemical, and material production and (b) conversion of CO2 to Omega-3 Fatty Acids.

i. **Photosynthesis**: Algae absorb sunlight through chlorophyll and pigments, converting CO_2 and water into glucose and oxygen by using energy
ii. **Biomass Accumulation**: Algae rely on glucose for their development and the accumulation of biomass, which involves the storage of energy in the form of lipids, carbohydrates, or proteins.

Algal cultivation has extensive applications in the production of biofuels, chemicals, and other materials.

4 **Biofuel Production**: Algae have the potential to generate various biofuels and provide a sustainable alternative to fossil fuels.
   i. **Biodiesel**: High-lipid algae can be harvested and processed into biodiesel via transesterification.

Lipids + Methanol → Biodiesel + Glycerol

   ii. **Bioethanol**: High-carbohydrate algae can be converted to ethanol using yeast or other microorganisms.
   iii. **Biogas**: Anaerobic digestion of algal biomass produces biogas, a mixture of methane and CO_2, which is suitable for heating, electricity generation, and transportation fuel.

- **Chemical Production**: Algae can produce a variety of chemicals, including pigments, fatty acids, and bioactive compounds.
   i. **Astaxanthin**: Algae such as *Haematococcus pluvialis* can produce astaxanthin, a valuable antioxidant used in food supplements and aquaculture.
   ii. **Omega-3 Fatty Acids**: Microalgae like Schizochytrium and Nannochloropsis can produce omega-3 fatty acids, used in nutritional supplements and pharmaceuticals.
   iii. **Polysaccharides**: Algal polysaccharides, such as agar, carrageenan, and alginate, are used in food, pharmaceuticals, and biotechnology.

- **Material Production**: Algal biomass has the potential to be utilized in various industries, such as packaging, agriculture, and bio-composites for processing and application.
   i. **Bioplastics**: Algal polysaccharides and proteins can be used to create bioplastics, providing a sustainable alternative to traditional plastics.

Biomass → Bioplastics

   ii. Biochar: Pyrolysis of algal biomass can yield biochar, a carbon-rich material utilized as a soil amendment and for carbon sequestration.

Biomass → Biochar

Biological and enzymatic conversion processes, like microbial fermentation and algal cultivation, offer sustainable and eco-friendly ways to convert CO_2 and renewable feedstocks into valuable products, utilizing the natural capabilities of microorganisms and algae.

3.4. Electrochemical conversion

Electrochemical conversion technologies, including electrolysis and CO_2 reduction, transform CO_2 into valuable products using electrical energy to drive chemical reactions These processes produce fuels, chemicals, and materials that address environmental challenges Fig. 9.

3.4.1. Electrolysis

Electrolysis converts CO_2 into products such as carbon monoxide (CO), methane (CH_4), and hydrocarbons, thereby supporting renewable energy systems and creating chemical feedstock. The basic setup involved an electrolytic cell with an anode and cathode to facilitate reactions. Applications include:

Carbon Monoxide (CO) is used in synthetic fuel production via the Fischer-Tropsch synthesis and in manufacturing chemicals such as methanol and hydrocarbons.

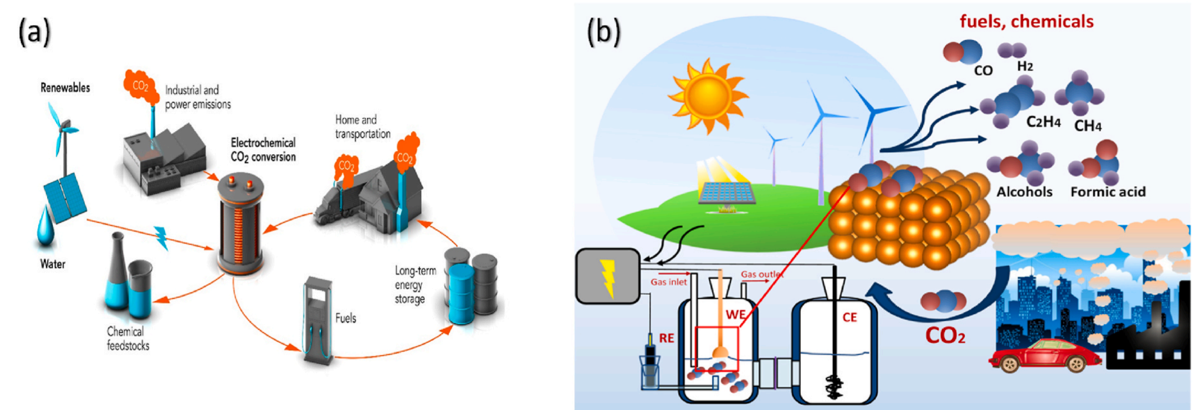

Fig. 9. Electrochemical conversion of CO2.

$CO_2 + 2H_2 \rightarrow CO + 2H_2O$

Methanol (CH_3OH): Utilized to produce formaldehyde, acetic acid, polymers, and as clean fuel or fuel cells.

$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

Ethylene (C_2H_4): Used in making polyethylene, ethylene glycol, and other chemicals and plastics.

$2CO_2 + 4H \rightarrow C_2H_4 + 2H_2O$

Formic Acid (HCOOH): Employed in food preservation, textiles, pharmaceuticals, and as a potential fuel or energy carrier.

$CO_2 + 2H^+ + 2e^- \rightarrow HCOOH$

Advancements in CO_2 electrolysis have focused on innovations in catalysts, electrolyzer design, and system integration. The key areas of innovation include the following.

i. **Metal-based Catalysts**: Copper-based catalysts are effective for reducing CO_2 to hydrocarbons and alcohols.
ii. **Composite Catalysts**: These combine metals with other materials to enhance their performance and stability.
iii. **Non-metal Catalysts**: Carbon and organic materials are used for CO_2 reduction.

High-performance electrolyzers are designed to improve efficiency, durability, and scalability (Brü et al., 2024). Integrating electrolysis with photovoltaic cells and other renewable sources enhances sustainability and economic viability by converting excess renewable energy into CO_2-derived products (Nnabuife et al., 2024a; Zapf and Wallek, 2022). Process optimization involves refining operational parameters and using real-time monitoring technologies to improve performance and yield (Singh, 2022). Proton exchange membrane (PEM) electrolyzers enhance the efficiency, durability, and scalability of CO_2 electrolysis (Fang et al., 2024). Hybrid systems combining CO_2 electrolysis with renewable energy sources, such as photovoltaic cells, can directly power CO_2 conversion processes, reduce fossil fuel reliance, and improve energy efficiency (Xin et al., 2024; Saleh, 2022).

- Carbon dioxide (CO) reduction

Carbon Dioxide Reduction (CO_2RR) is an electrochemical process that converts CO_2 into valuable products, such as fuels, chemicals, and materials, using electrical energy. This process can mitigate climate change by recycling CO_2 and by integrating renewable energy sources (Al Harthi et al., 2024; Zhao, 2024). This involves two reactions: the cathode reaction, which converts CO_2 to various products, and the anode reaction, which oxidizes water or other substances to generate oxygen or other by-products.

The applications of CO_2 Reduction include the following.

i. **Carbon monoxide**: used in Fischer-Tropsch synthesis for hydrocarbons and chemical processes.

$CO_2 + H_2 \rightarrow CO + H_2O$

ii. **Methanol**: CO_2 can be reduced to methanol, a versatile chemical and fuel, using a copper-based catalyst:

$CO_2 + 3H_2 \rightarrow CH_3OH + H_2OCO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

Methanol can be used as a fuel, chemical feedstock, or in fuel cells.

iii. **Formic Acid**: Formic acid, used in agriculture and industry, can be produced from CO_2:

$CO_2 + 2H^+ + 2e^- \rightarrow HCOOHCO_2 + 2H^+ + 2e^- \rightarrow HCOOH$

Formic acid has applications in food preservation, textiles, and pharmaceuticals.

iv. **Ethylene**: Ethylene, a key precursor for plastics and chemicals, can be produced from CO_2:

$2CO_2 + 4H_2 \rightarrow C_2H_4 + 2H_2O_2CO_2 + 4H_2 \rightarrow C_2H_4 + 2H_2O$

Ethylene is used in the production of polyethylene, ethylene glycol, and other chemicals.

Research has focused on designing metal-based catalysts, such as copper, silver, and gold, for the efficient, selective, and stably convert CO_2 into specific products (Franco et al., 2020). Advancements in electrochemical conversion aim to improve efficiency, scalability, and integration with renewable energy sources (Sajna et al., 2023). Innovations include advanced catalysts (e.g., nanomaterials, alloyed catalysts, and engineered enzyme systems), integrated systems, process optimization (e.g., high-performance electrolyzers and reactor designs), and digitalization and automation for real-time monitoring, control, and optimization (Bollini et al., 2023; Dwivedi et al., 2022). Electrochemical conversion technologies, such as electrolysis and CO_2 reduction, are crucial for addressing climate change and resource challenges by utilizing electrical energy for sustainable fuel, chemical, and material production (Detz et al., 2023; Grim et al., 2020). (Tao et al., 2024) developed a new electrocatalyst to produce formate (HCOOH) during electrochemical carbon dioxide reduction. Snowflake-like Cu_2S increased carbon dioxide concentration and promoted CO_2 binding with SnO_2. Carbon spheres enhanced electron transport and converted CO_2

into HCOOH, and snowflake-like Cu_2S loaded with 1 wt% SnO_2@C had an 88% HCOOH Faraday Efficiency and a stable current density for CO_2 reduction (Yan et al., 2024). presented an electrochemical reconstruction of ultrafine Cu_2O nanodomains on a CeO_2 surface, which served as an electrocatalyst for CO_2 reduction. The Cu_2O/CeO_2 catalyst exhibited a selectivity of over 49% towards CH_4 over a broad potential range, maintaining minimal activity decay for 20 h. The highest CH_4 selectivity was 70% at −1.5 V vs. RHE (Shen et al., 2025). demonstrated the use of nitrogen to adjust the Cu^0 and Cu^+ sites in Cu_2O catalysts, enhancing C2-product conversion. The Cu^0/Cu^+ ratio of the Cu_2O catalyst was controlled by adjusting the amount of N doping using NH_3/Ar plasma treatment. The study also clarified the ethylene Faraday efficiency volcano curve, determining the optimal Cu^0/Cu^+ ratio of 0.43 for selective CO_2 to ethylene conversion (Song et al., 2024). prepared g-C_3N_4-PDI (CNP) and MOF-545-NH_2 (MNH) using calcination and hydrothermal methods, respectively. CNP/MNH photocatalysts were created by in situ growth of MNH on the CNP surface. The photocatalytic CO_2 conversion reaction was tested using triethanolamine and aniline solutions. The CNP/MNH catalyst exhibited excellent performance, yielding a high amount of CH_4 with triethanolamine as a sacrificial agent, and some CO_2 was converted to ethanol.

3.5. Advantages and challenges of each conversion approach

Conversion Approach	Advantages	Challenges	Possible Solutions	Reference
Electrochemical conversion	The process offers versatility, renewable integration, high purity, and direct conversion of CO_2 with minimal by-products, allowing for the production of various products, such as CO, CH_3, and methanol	High electricity costs, expensive catalysts, and industrial scaling pose significant challenges to the overall process efficiency	The integration of low-cost or renewable energy sources, development of cost-effective catalysts, process design optimization, and investment in research are crucial for reducing electricity costs	(Bellini et al., 2022; Garg et al., 2020; Ahmed et al., 2022)
Chemical conversion	High efficiency, established technology, scalability, and diverse products make this process ideal for industrial production	This process is energy-intensive and requires significant energy inputs, potentially causing negative environmental impacts, requires complex processes and equipment, and is reliant on fluctuating raw material costs	The strategy involves enhancing energy efficiency by researching and implementing energy-saving technologies, transitioning to renewable energy sources, simplifying processes, and exploring alternative, sustainable raw materials	(Clomburg et al., 2017; Carmona-Martí et al., 2024b; Osman et al., 2024)
Biological conversion	Sustainability, low energy input, biomimetic efficiency, and resource recovery are the key benefits of using renewable feedstocks and natural processes	Biological processes can be slow and require precise environmental control for scale-up, and complex conditions can lead to mixed products that require further separation	Genetic and metabolic engineering can accelerate biological processes, and scalable systems can be developed for larger operations. Control systems can be refined to achieve optimal conditions, and advanced separation and purification technologies have been developed	(Liu et al., 2024a; Baskaran et al., 2024; Ji et al., 2024)
Electrolysis	Clean hydrogen production minimizes the environmental impact, offers energy storage for excess renewable energy, is adaptable to various scales, and can be integrated with renewable sources	High capital and electricity costs, moderate energy efficiency, and substantial infrastructure needs for hydrogen storage are significant challenges in current electrolytic processes	Reduce cost-effective materials and designs, integrating renewable energy, improving the efficiency of electrolyzer designs, and investing in infrastructure development for hydrogen storage and distribution to reduce capital costs	(Song et al., 2024; Kamran and Turzyński, 2024; Nnabuife et al., 2024b)
Direct air capture (DAC)	The device offers versatility, scalability, high-purity CO_2 capture and can be combined with various conversion technologies for large-scale deployment	High costs, energy intensity, limited infrastructure, and low efficiency of low-concentration CO_2 capture make it a challenging and expensive solution	Project aims to reduce costs; enhance energy efficiency; build infrastructure for CO_2 capture, transport, and storage; and improve methods for capturing low-concentration CO_2	(Hu et al., 2024; García-Bordej et al., 2024a; Li and Yao, 2024)
Industrial capture systems	High-efficiency, established technology targets CO_2 streams, integrates with existing industrial processes, and directly utilizes CO_2 from processes for product recovery	This technology is limited to specific industries, has high operational costs, requires significant infrastructure, and relies heavily on existing industrial sources	Expand applicability, reduce operational costs, invest in infrastructure, and diversify sources to reduce CO_2 emissions across diverse industries	(Raganati and Ammendola, 2024; Yagmur Goren et al., 2024)

(continued on next column)

4. Applications and value-added products

4.1. Carbon-neutral fuels: synthetic gasoline, diesel, and aviation fuel

The push for carbon-neutral fuels has gained momentum as a critical strategy to combat climate change and reduce greenhouse gas emissions from the transportation sector. Among these fuels, synthetic gasoline, diesel, and aviation fuel hold significant promise due to their compatibility with existing infrastructure and potential for large-scale production.

4.1.1. Synthetic gasoline

Synthetic gasoline is produced through processes such as Fischer-Tropsch synthesis, which converts syngas—a mixture of carbon monoxide and hydrogen derived from renewable sources—into liquid hydrocarbons. This fuel can be used directly in internal combustion engines designed for conventional gasoline, thus offering a seamless transition to more sustainable fuel options. Studies have demonstrated that synthetic gasoline, when blended with alcohols like ethanol, can improve engine performance and reduce emissions of pollutants (Modupe Abati et al., 2024). Additionally, synthetic gasoline blends with dimethyl carbonate have shown promising results in spray dynamics and combustion efficiency (Huang et al., 2023).

4.1.2. Synthetic diesel

Synthetic diesel, similar to synthetic gasoline, is produced via Fischer-Tropsch synthesis and other methods such as hydroprocessed esters and fatty acids (HEFA). It can be used in diesel engines without modifications, making it a viable option for reducing emissions from heavy-duty vehicles and machinery. Research indicates that synthetic diesel can achieve lower emissions of particulate matter and nitrogen oxides compared to conventional diesel, while maintaining high energy efficiency (Salahi et al., 2022). The adoption of synthetic diesel is further supported by advancements in exhaust gas analysis techniques, which help optimize its performance and environmental benefits (Kraus et al., 2022).

4.1.3. Synthetic aviation fuels

The aviation industry, a significant contributor to global CO_2 emissions, is exploring synthetic aviation fuels (SAFs) as a crucial part of its decarbonization strategy. SAFs can be produced from a variety of feedstocks, including biomass and captured CO_2, through processes such as Fischer-Tropsch and power-to-liquid (PtL) technologies. These fuels have been shown to reduce life-cycle carbon emissions by up to 80% compared to conventional jet fuel (Liu et al., 2022b). Moreover, SAFs can be blended with traditional jet fuels, facilitating their adoption in existing aircraft with minimal adjustments. The versatility and environmental benefits of SAFs make them a key component of future sustainable aviation practices (Jin et al., 2023) In addition to their primary use as fuels, synthetic gasoline, diesel, and aviation fuel can generate various value-added products. For instance, the by-products of Fischer-Tropsch synthesis, such as naphtha and waxes, can be used in the chemical industry to produce plastics, lubricants, and other materials (Buthelezi et al., 2024). Furthermore, the integration of synthetic fuel production with carbon capture technologies not only helps in reducing atmospheric CO_2 but also provides a source of raw materials for other industrial processes (Moreno-Gonzalez et al., 2021) The development and adoption of synthetic gasoline, diesel, and aviation fuel represent a significant step towards achieving carbon-neutral transportation. These fuels offer a compatible and sustainable alternative to conventional fossil fuels, with the added benefit of generating valuable by-products. Continued research and policy support are essential to overcoming the current technological and economic challenges, paving the way for widespread implementation of these innovative solutions.

4.2. Chemical feedstocks: methanol, ethylene, and formic acid

The utilization of methanol, ethylene, and formic acid as chemical feedstocks plays a crucial role in various industrial processes, providing a foundation for the production of a wide range of value-added products. This review highlights the applications and benefits of these feedstocks in modern industry.

4.2.1. Methanol

Methanol is a versatile chemical feedstock used extensively in the production of formaldehyde, acetic acid, and a variety of other chemicals (Kibria et al., 2019). One of its significant applications is in the production of biodiesel through transesterification, which is an environmentally friendly alternative to traditional fossil fuels (Andika et al., 2018). Methanol is also pivotal in the manufacture of methyl tert-butyl ether (MTBE), a gasoline additive that enhances combustion efficiency and reduces engine knocking (Tabibian and Sharifzadeh, 2023).

Methanol is increasingly being explored for its potential in renewable energy applications, particularly in fuel cells. Methanol fuel cells offer a clean energy source with higher energy density compared to hydrogen fuel cells (Kappis et al., 2021). The electrochemical reduction of CO_2 to methanol using renewable energy sources presents a promising route for sustainable fuel production and CO_2 utilization (Wang et al., 2020). Additionally, methanol can be used in the production of olefins through the methanol-to-olefins (MTO) process, which provides a route to produce valuable petrochemicals from non-petroleum sources (Mei et al., 2022).

4.2.2. Ethylene

Ethylene is a fundamental building block in the petrochemical industry, primarily used in the production of polyethylene, which is one of the most widely used plastics in the world (Chen et al., 2020). It serves as a precursor for producing ethylene oxide, which is subsequently converted into ethylene glycol, an important component in antifreeze and polyester production (Fan et al., 2023; Chauhan et al., 2023)). The versatility of ethylene extends to the synthesis of various polymers and copolymers used in packaging, automotive parts, and consumer goods.

Advanced catalytic processes have enabled the efficient conversion of ethylene into a wide range of chemical products, enhancing its value as a feedstock (Chauhan et al., 2023) The development of catalysts that improve the selectivity and yield of ethylene-based reactions has significant implications for the production of high-value chemicals and materials (Fan et al., 2023; Keijzer et al., 2024; Lamichhane et al., 2024).

4.2.3. Formic acid

Formic acid is utilized in various industrial processes, including as a preservative and antibacterial agent in livestock feed, a coagulant in rubber production, and a reducing agent in textile dyeing and finishing (Bejigo et al., 2023). It is also used in the leather industry for tanning and in the production of formate salts, which have applications in de-icing and drilling fluids (Chilakamarry et al., 2021).

One of the emerging applications of formic acid is in the field of renewable energy. Formic acid can be used in fuel cells as a hydrogen carrier, providing a safer and more manageable alternative to hydrogen gas (Nie et al., 2023) The electrochemical conversion of CO_2 to formic acid is a promising technology for CO_2 utilization, offering a pathway to produce a valuable chemical while mitigating greenhouse gas emissions (Fu et al., 2022; Chauvy et al., 2019).

4.3. Carbon-neutral concrete, polymers, and aggregates

The construction industry is increasingly focused on sustainability, prompting the development and application of carbon-neutral concrete, polymers, and aggregates. These materials not only reduce environmental impact but also offer enhanced performance and new value-added products.

4.3.1. Carbon-neutral concrete

Carbon-neutral concrete is a revolutionary building material designed to reduce the carbon footprint of construction. One approach to achieving carbon neutrality in concrete is the incorporation of industrial by-products, such as fly ash and slag, which can replace a significant portion of Portland cement (Dos Reis et al., 2021) This method not only cuts down on carbon emissions but also enhances the mechanical properties and durability of the concrete (Dos Reis et al., 2021) Another innovative technique is the use of CO2 curing, which involves injecting carbon dioxide into the concrete mix, leading to the formation of stable carbonates that enhance strength and durability (Bandara et al., 2023). Carbon-neutral concrete is being explored for various applications, including structural components, road construction, and precast concrete products (Silva et al., 2019).

4.3.2. Polymers

Polymers in construction are primarily used for their durability, flexibility, and resistance to environmental factors. Polymers such as polyethylene and polypropylene are utilized in construction materials like pipes, insulation, and roofing membranes (Zhang et al., 2020). The use of recycled plastics in concrete as partial aggregates or fibers has shown to improve the toughness and crack resistance of the material, while also contributing to waste reduction (Mechtcherine et al., 2021) Additionally, advanced polymers are being developed for use in smart materials and coatings that can respond to environmental changes, thereby enhancing the energy efficiency and longevity of buildings (Mechtcherine et al., 2021).

4.3.3. Aggregates

Aggregates are essential components of concrete, providing structural integrity and bulk. The use of recycled aggregates from construction and demolition waste is a sustainable practice that reduces the demand for natural aggregates and minimizes landfill waste (Salesa et al., 2022). Studies have shown that recycled aggregates can achieve performance levels comparable to natural aggregates when appropriately processed and used (Salesa et al., 2022) Furthermore, specialized aggregates, such as lightweight and high-density aggregates, are being developed for specific applications, including high-performance concrete and radiation shielding (Nguyen et al., 2022) The integration of recycled and innovative aggregates into concrete not only supports environmental sustainability but also opens up new avenues for advanced construction materials (Nguyen et al., 2022).

4.4. Food and agriculture: algal biomass for food supplements, CO2-Derived fertilizers

4.4.1. Algal biomass for food supplements

The utilization of algal biomass in food supplements has garnered significant interest due to its rich nutritional profile and potential health benefits. Algal biomass, particularly microalgae, is recognized for its high protein content, essential fatty acids, vitamins, and minerals, making it a promising ingredient for enhancing the nutritional quality of food products (Becker, 2013). The incorporation of algal biomass into food supplements can address dietary deficiencies and promote overall health and well-being (Shah et al., 2016).

One of the key advantages of algal biomass is its ability to produce bioactive compounds that exhibit antioxidant, anti-inflammatory, and antimicrobial properties. These bioactive compounds can enhance the functional properties of food supplements, providing additional health benefits beyond basic nutrition. For instance, spirulina, a type of blue-green algae, is widely used in food supplements due to its high protein content and bioactive compounds that support immune function and reduce oxidative stress (Chauvy and De Weireld, 2020; Lu et al., 2021; El-Shall et al., 2023; Gogna et al., 2023).

In addition to its nutritional and bioactive properties, algal biomass is sustainable and environmentally friendly. Microalgae can be cultivated using non-arable land and non-potable water, making it a viable option for sustainable food production (Spolaore et al., 2006) Furthermore, the cultivation of microalgae for food supplements can contribute to carbon sequestration, as algae utilize carbon dioxide during photosynthesis, thereby reducing greenhouse gas emissions (Huang et al., 2018).

4.4.2. CO_2 – derived fertilizers

CO_2-derived fertilizers are another innovative application in the field of agriculture. These fertilizers are produced by capturing carbon dioxide from industrial processes and converting it into valuable agricultural inputs. The use of CO_2-derived fertilizers can enhance crop yield and quality while simultaneously mitigating the environmental impact of industrial CO_2 emissions (Sanz-Cobena et al., 2017).

CO_2-derived fertilizers provide essential nutrients to plants, such as nitrogen, phosphorus, and potassium, which are crucial for plant growth and development. These fertilizers can improve soil fertility, enhance nutrient uptake by plants, and increase agricultural productivity (Hosseini and Wahid, 2016). Additionally, the utilization of CO_2-derived fertilizers can reduce the dependency on traditional chemical fertilizers, which are associated with environmental issues such as soil degradation and water pollution (Fu et al., 2022; Liu et al., 2021).

The development and application of CO_2-derived fertilizers also present an opportunity for the circular economy in agriculture. By utilizing waste CO_2 as a resource, these fertilizers contribute to a closed-loop system that minimizes waste and maximizes resource efficiency (Sanz-Cobena et al., 2017). This approach aligns with the principles of sustainable agriculture and supports the transition towards more environmentally friendly farming practices.

In summary, the applications and value-added products of algal biomass and CO2-derived fertilizers offer significant potential for enhancing food and agricultural systems. Algal biomass provides a sustainable and nutritionally rich source for food supplements, while CO_2-derived fertilizers present an innovative solution for improving crop productivity and environmental sustainability. These advancements highlight the importance of integrating sustainable practices and innovative technologies in the pursuit of food security and environmental conservation.

4.5. Economic and environmental benefits of utilizing CO_2-Derived products

The utilization of CO_2-derived products offers significant economic and environmental benefits, playing a crucial role in mitigating climate change and enhancing industrial sustainability.

4.5.1. Economic benefits

CO_2-derived products can substantially reduce the costs associated with carbon emissions by transforming CO_2 from a waste product into a valuable raw material (Liu et al., 2021, 2024b) This transformation process can create economic opportunities across various industries, including construction, agriculture, and energy. For instance, the use of CO_2 in producing building materials, such as concrete and polymers, can lower the production costs while simultaneously reducing the carbon footprint of these materials (Bolotova, 2023).

The production of CO_2-derived fertilizers can enhance agricultural productivity and reduce dependence on traditional chemical fertilizers, which are often associated with high costs and environmental degradation (Elaouzy and El Fadar, 2022) By utilizing waste CO_2, these fertilizers provide an economically viable solution for improving soil fertility and crop yields (Elaouzy and El Fadar, 2022).

In the energy sector, CO_2-derived fuels and chemicals can offer a sustainable alternative to fossil fuels, reducing the economic impact of fuel production and consumption (Zhang et al., 2023) The development of technologies for CO_2 conversion can also stimulate job creation in green industries and promote economic growth through innovation and investment in sustainable practices (Humpenö et al., 2022).

4.5.2. Environmental benefits

The environmental benefits of CO_2-derived products are substantial, as they contribute to the reduction of greenhouse gas emissions and the mitigation of climate change. By capturing and converting CO_2 emissions from industrial processes, these products help to decrease the overall carbon footprint of various industries (Bolotova, 2023).

CO2-derived materials, such as polymers and construction aggregates, can replace traditional materials that are often produced through environmentally harmful processes (Wang et al., 2024b) For example, CO_2-derived concrete and other building materials not only reduce CO_2 emissions but also improve the sustainability of construction practices by utilizing waste products and reducing the need for virgin materials (Bolotova, 2023).

The use of CO_2-derived fertilizers can enhance soil health and reduce the environmental impact of agricultural practices. Traditional fertilizers often lead to soil degradation and water pollution, whereas CO_2-derived fertilizers offer a more sustainable alternative by promoting nutrient recycling and reducing the need for chemical inputs (Elaouzy and El Fadar, 2022).

Moreover, the development and application of CO_2-derived products align with the principles of the circular economy, promoting resource efficiency and waste reduction. This approach supports the transition towards more sustainable industrial practices and contributes to the conservation of natural resources (Shang et al., 2021).

5. Demonstrating success: case studies and quantitative evidence

5.1. Pilot projects and commercial ventures: climeworks, Carbon Engineering, LanzaTech

5.1.1. Climeworks, Carbon Engineering, and LanzaTech: pioneers in carbon management

These three companies are at the forefront of developing and commercializing technologies to capture and utilize carbon dioxide (CO_2). They may have similar objectives, but their methods and geographical coverage differ, as seen in Table 2.

Table 2
The main differences between Climeworks, LanzaTech, and Carbon Engineering.

Features	Climeworks	LanzaTech	Carbon Engineering
Primary focus	Direct air capture (DAC)	Carbon recycling (gas fermentation)	Direct air capture (DAC) and Carbon conversion
Feedstock	Ambient CO_2	Industrial waste gas (CO, H2)	Ambient CO_2
Technology	Solid sorbent-based DAC	Microbial fermentation	Liquid-based DAC and conversion to fuels.
End-products	Capture CO_2 for storage or utilization	Ethanol, other chemical fuels	Captured CO_2, synthetic fuels
Commercialization stage	Advanced, multiple commercial-scale plants	Commercializing in various regions	Scaling up commercial operations
Focus	Permanent CO_2 removal	CO_2 utilization and waste reduction	CO_2 removal and potential fuel production
Maturity	More commercially developed	Earlier stage of development	Earlier stage of development
Challenges	High energy consumption, cost reduction	Optimization process efficiency, market development for the product	High energy consumption, cost reduction
Opportunities	Growing Carbon offset market, CO_2 utilization potential	Waste reduction in industries, development of sustainable fuels.	CO_2 removal contribution for carbon-neutral fuel
Synergy	Captured CO_2 from this process can be utilized by LanzaTech or Carbon engineering	Not applicable	Captured CO_2 from this process can be utilized by LanzaTech.

5.1.2. Climeworks: direct air capture (DAC)

Climeworks has adopted several direct air capture (DAC) plants globally, in countries including Iceland, Switzerland, and Canada. These plants capture CO_2 directly from ambient air and store it underground (Bisotti et al., 2024) (see Fig. 10). The company has also partnered on projects to utilize captured CO_2 for enhanced mineral carbonation and carbonated beverages. It is used for developing and scaling the DAC technologies with suitable data for refining their process (García-Bordej et al., 2024b). It captures CO_2 from the atmosphere and offers various applications to the consumer. Wang et al. (2024c) reported that there are 19 DAC facilities with operations globally producing 10, 000 t of CO_2 which is less than the 350 Mt of air-captured CO_2 in application synthetic fuels in 2050. They further explained the impurities of the CO_2 stream led to an extra engineering cost. The liquid fuel, Carbon collects, and MOF-74 nanocomposite contains 50 %, 95 %, and 70–80 % purity of CO_2. The purity of CO_2 produced depends on the following factors: 1) system design 2) the sorbent used and 3) the facility scale. Bissotti et al. (Bisotti et al., 2024) suggested that the progress of DAC deployment depends not just on technical requirements but finances, political and social sciences are critical factors to be considered. They further pointed out that the system capacity should be improved to 0.1 M tCO_2 per year for adsorption of DAC and 1.0 M tCO_2 per year for liquid-DAC with operation within 7 years of construction. Sievert et al. (2024) pointed out that the future of DAC plants will be different from the current designs with the incorporation of new or replacing existing components. For instance, Carbon Engineering filed a patent application for bipolar membrane electrodialysis (BPMED), reducing the need for pillet reactor. Boerst et al. (2024) proposed the use of NGGC plants to power DAC in the USA to repurpose the assets that would have been retired and boost local economies that are impacted by decarbonization. They suggest for the need to investigate the use low low-carbon technology power sources like nuclear and renewable energy which becomes a critical geographical factor in siting DAC plants like energy storage, solar and wind corridor as well as nuclear power plants. Ottenbros et al. reported (Ottenbros et al., 2024b) the burden and benefits of DACC on the commercial scale in terms of quality of the ecosystem, human health, and climate change for capturing and storing 1 tonne of CO_2. Regardless of energy generation configuration and background scenario, the environmental benefits outweigh the costs of constructing and maintaining the DACCS system for harm to ecosystems and climate change. On the other hand, the benefits to human health increase only if external developments align with keeping warming to 2 °C or less than 1.5 °C, and only if the costs associated with grid-connected and hybrid electricity arrangements are also greater. Examining contributions reveals that the primary effect categories that harm human health and ecosystems are climate change, human toxicity, and the creation of fine particulate matter. Gutsch and Leker (2024) reported that the Utilization gets close to 100% if sufficient extra PV power and storage capacity are installed, as demonstrated by the "200–300" combination in Nevada. The off-grid CO2 removal process could become unaffordable due to the greater upfront costs involved with huge energy systems. Environmental effects are also linked to the energy system's production. Emissions of greenhouse gases from the energy system's life cycle reduce CRE, which raises the price of net CO2 removal. Other environmental effects should be minimized under the principles of sustainable development, even though they do not immediately result in increased expenses. They further reported the annual cost of 100 $KtCO_2$ per year off-grid DAC system in Nevada. The annual cost of the adsorbent material with the amount of the captured CO_2 because of the degradation of the adsorbent material is directly proportional to the amount of CO_2 captured.

5.1.3. LanzaTech: carbon recycling

LanzaTech has developed and deployed gas fermentation technology

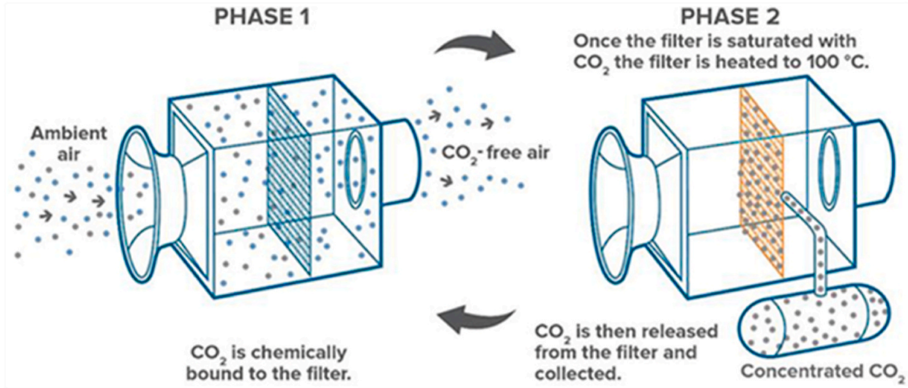

Fig. 10. The process of the climeworks direct air capture (DAC) (Beuttler et al., 2019). Copyrights by Frontiers @2019.

(see Fig. 11) to convert industrial waste gases, including those containing CO_2, into ethanol and other chemicals (Mihalcea et al., 2023; Quataert et al., 2023). The company is well-known for having several pilot and demonstration projects in operation around the world (Sobieraj et al., 2022). LanzaTech has partnered with major industrial companies to build commercial-scale facilities to produce sustainable fuels and chemicals. It is expanding its technology to solve a range of waste gases and specific products. There are two main pilot plants: 1. Municipal Solid Waste (MSW) to ethanol: It is portioned with Sekisui chemicals to develop pilot plants that convert syngas from MSW into ethanol. This project demonstrates the potential of gas fermentation to address waste management and produce valuable products (Kö et al., 2020). Nabila et al. (2024) reported that MSW was used as a substitute for gasoline with the potential significance reduce greenhouse gas emissions from 29.2 to 86.1 %. They further reported that MSW paper and grass chipping were mixed with corn stover to produce biofuel at operation cost US $72.83 to US $72.26. Arias et al. (2024) reported edible oil-crop are used as feedstocks to produce 95 % biodiesel called first-generation biofuel while those obtained from non-food feedstocks are second-generation biofuel then finally the use algae to produce biofuel and it has superior advantages because it has cheaper production processes, higher feedstocks availability, remarkable productivity of 15–3000 better to other generations of biofuels.

Royle et al. (2024) A fermentation technique can also be used to turn pre-treated waste biomass into ethanol. Even though over 5 billion liters of bioethanol are generated annually in Europe from biomass feedstocks, most of that ethanol is first-generation ethanol made from feedstock made of beet sugar.28 Alternatively, wood, food waste, low-quality crops, and sewage sludge are used as feedstocks for biomass waste. 2. Carbon dioxide to High-value lipids: It collaborates with oil to convert carbon dioxide to lipids with biofuel application (Waltz, 2024). Through strain performance optimization, biotechnological approaches have increased the efficiency of butanol synthesis. The creation of strains to produce butanol has concentrated on features such as butanol productivity and selectivity in lignocellulosic biomass waste, enhanced substrate utilization, and butanol tolerance. In batch fermentation, Clostridium strains can withstand butanol concentrations as low as 2% (v/v) and usually produce less than 13 g/L of butanol. Butanol has a complicated toxicity profile to microbial systems that impact a range of cellular functions. Clostridium spp. create butanol, which reduces cellular proton motive force and electrochemical potential, fluidizes the phospholipid layer to disturb membrane stability, and inhibits ATPase function. All of these effects occur when ions can pass through the membrane (Nabila et al., 2024). Raj et al. (2024) reported that young

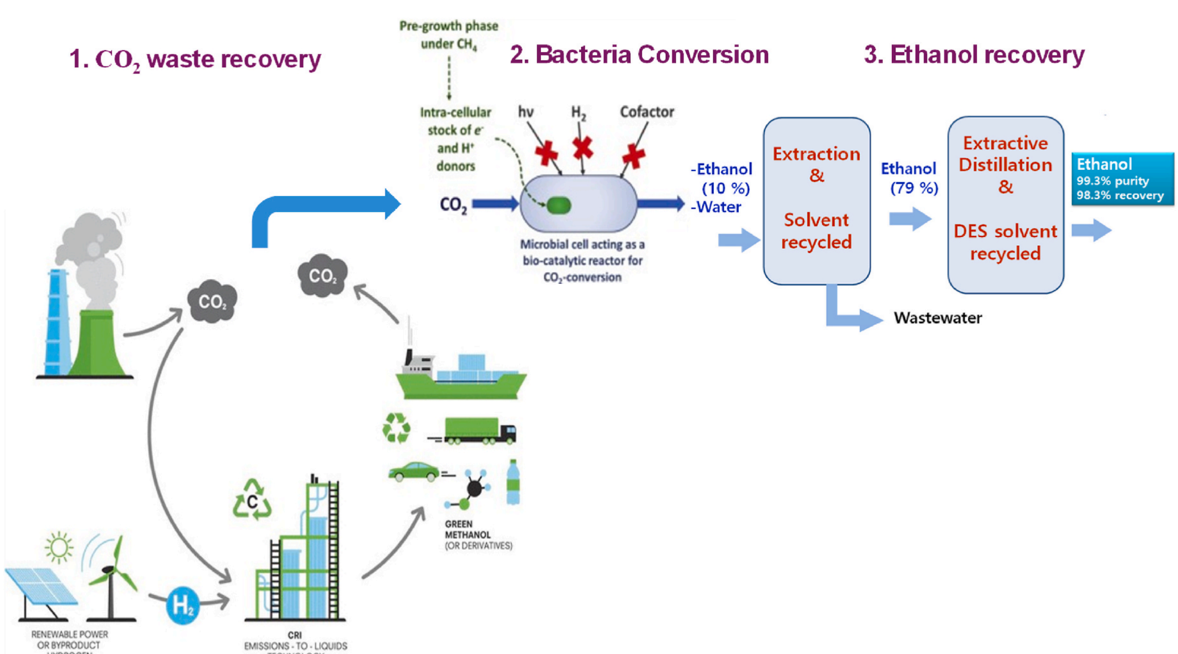

Fig. 11. The operation of gas fermentation.

and new forest absorbs about 30 % CO_2 from the atmosphere which is significant in biomass remains in mass. Therefore, afforestation is critical because young trees grow faster and absorb much less carbon with smaller photosynthetic surface area. The death of trees through pests or diseases or aging will result in a decline in the rate of carbon uptake. Mishra et al. (2024) demonstrated that the degree of codon optimization influences product biosynthesis in an engineered organism by employing two codon-optimized forms of the thioesterase, BTE, to demonstrate C12-fatty acid production in C. necator. The titers decreased after 24 or 48 h due to fatty acid consumption, even though we were able to create approximately 100 mg/L of dodecanoic acid. Finding and eliminating more β-oxidation genes is crucial because even in strain H16-6895, where β-oxidation operons A0459–A0464 and A1526–A1531 were removed, the oleochemical compounds were catabolized at later times. This corresponds with a recent study that found that several other β-oxidation genes are expressed when the H16-6895 strain is grown in a medium containing medium-chain-length fatty acids (Strittmatter et al., 2023).

5.1.4. Carbon Engineering: direct air capture and carbon conversion

Carbon Engineering has built a large-scale pilot plant in Squamish, British Columbia, Canada. Carbon Engineering is partnering with industrial companies to develop commercial-scale facilities for producing low-carbon fuels and chemicals. The company is also exploring opportunities for carbon storage and utilization. There have not been any fully commercialized Carbon engineering ventures involved in operational globally but some of the nations developing and deploying these technologies. This facility demonstrates the company's technology for capturing CO_2 from the atmosphere and converting it into transportation fuels and other products (Barahimi et al., 2023). This uses 3 basic technologies.

5.1.5. Direct air capture (DAC): the captured CO_2 is successfully removed from the ambient air

Fuel synthesis: The conversion of the captured CO_2 into transportation fuel, showing the potential for creating carbon-neutral fuel (Ló et al., 2024). García-Bordejé, and González-Olmos (García-Bordej et al., 2024b) reported that the utilization of DAC technology is motivated by the ability to transform captured CO_2 into valuable products. Two primary categories of chemical products can be produced from CO_2 conversion: those that come from a redox reaction that needs a hydrogenating agent and those that come from a non-redox reaction that can produce urea, carbamates, organic carbonates, and inorganic carbonates. The products of non-redox reactions are currently produced from fossil fuels. The market demand for these chemicals is much lower than that for fuels and chemicals such as oxygenates, alkanes, and olefins. Fuels for transport can be also produced starting from CO_2 via CO, methanol, methane or light olefins intermediates. Electrofuels, commonly referred to as e-fuels since their carbon neutrality is guaranteed by capturing spent CO_2 from the atmosphere, are CO_2-based hydrocarbons that are created using renewable electricity and water. Because biofuels are less sustainable and have a restricted supply of feedstock, which limits their scalability, e-fuels are becoming more significant. Furthermore, it is possible to tune the DAC process to capture both CO_2 and the H_2O required for the synthesis of e-fuels. Shao et al. (2024) reported the process known as "Carbonate Dry Reforming of Methane (CaDRM)" uses a reaction between methane (CH4) and limestone (CaCO3) to directly produce cement clinker precursor (CaO) and syngas ($CO + H_2$). Thermodynamic research shows that as compared to $CaCO_3$ thermal decomposition, the reaction temperature of CaDRM is at least 200 °C lower. Utilizing cement raw meal at 700 °C, lab-scale experimental investigations demonstrate a 90 % CH4 conversion and a 95% CaO production at 91 % syngas selectivity in CaDRM. Comparing the CaDRM approach to the traditional CaCO3 thermal decomposition pathway, process simulation scale-up, and economic analysis show that the former can lower CO_2 emissions by 37.2 %. More importantly, the value-added syngas products and energy savings can be used to reach a net profit of $271.0/t (clinker). Postweiler et al. (2024) reported a portion of the CO_2 that is captured by a DACCS system from the environment ($m_{co2,cap}$) is placed in permanent storage ($m_{co2,sto}$) (Fig. 12). The mass flow of purified CO_2 that exits the DAC plant is described in our work by the amount of captured CO2 ($_{mco2,cap}$). Due to leaks in CO_2 transportation and storage, not all of the captured CO_2 is kept indefinitely. The DACCS system releases GHGs both directly and indirectly to absorb CO_2. It also needs total work (W_{total}) and total heat (Q_{total}). The impact of these GHGs on climate change (CC) is measured in CO_2 equivalents.

A Collaborative initiatives: CO_2 Value Europe, Carbon Utilization Research Council (CURC)

5.1.6. CO_2 Value Europe (CVE)

CO_2 Value Europe (CVE) is a non-profit organization dedicated to promoting Carbon capture and Utilization (CCU) technologies across Europe. It is a platform for stakeholders in the CCU value chain, including industries, startups, research institutions, and policymakers. It is important to accelerate CCU technology to contribute to a future for Europe (Position paper CVE CCU in, 2022). Chauvy and Weireld (2020) reported CO_2 utilization is naturally converted by photosynthesis with wide application in dry cleaning, the food industry, and extraction of compounds with supercritical CO_2. This showed that renewable sources of carbon-free from renewable sources can be converted into useful commodity materials, chemicals, and fuels. CVE also has an initiative in the deployment and development of large-scale CO_2 conversion processes in Europe. The capturing and converting of CO_2 from a wide range of emissions sources include 5–12 % energy generation sources, 15 % industrial sources, 14–33 % cement factories, and 0.04 % directly from the air, enabling the development and deployment of new technologies with the potential to mitigate CO_2 emissions. Mias et al. (2020) reported the political and physical collaboration in the European power market with emphasis on costs and benefits to CO_2 emissions of 90–139 Mt, abatement cost and benefits of 245–271 EUR/ton CO_2 and prices of 57–67 EUR/MWh in 2050 for the most collaborative narrative while the emission 848–1013 Mt, cost of 378–559 EUR/ton and electrical prices 47–57 EUR/MWh for the least collaborative ones. They further observed that countries at the outskirts of the European market seem to experience lower prices and abate more but prices are higher and abatement lower in Central and South-East Europe.

5.1.7. Carbon Utilization Research Council (CURC)

The Carbon Utilization Research Council (CURC) is primarily a US-based and industry-driven coalition, with a focus on utilizing fossil fuels responsibly. The stakeholders or membership includes power generators, technology developers, labor unions, industry associations, fossil fuel producers, non-governmental organizations (NGOs), and research organizations. They collaborate and promote research, development, and deployment of CCU technologies for utilizing fossil energy resources sustainably (Carbon Utilization Research Council (CURC) and Carbon Utilization Research Council (CURC), 2024). Yuan et al. (Yuan and Lyon, 2012) reported a collaboration between US and China for Carbon capture and storage (CCUS) because they are the world's largest greenhouse gas emitters. They are collaborating to produce clean and common energy security to solve their differentiated economic and development challenges with benefits to the US such as acceleration in technology, job creation, reduction of electrical prices, and saving cost. Waxman et al. (2021) reported the CCUS in the gulf clusters which shows that the CCUS cost is equivalent to the social cost of carbon with the effect that the US Federal tax incentives which have been put in place till 2026 would justify 3.3–77.6 million tonnes of annual CCUS in the region depending on the choice of technology of storage and the degree of pipeline network coordination. Frank-Collins et al. (Frank-collins et al., 2022) reported the initiative of the goal of the US

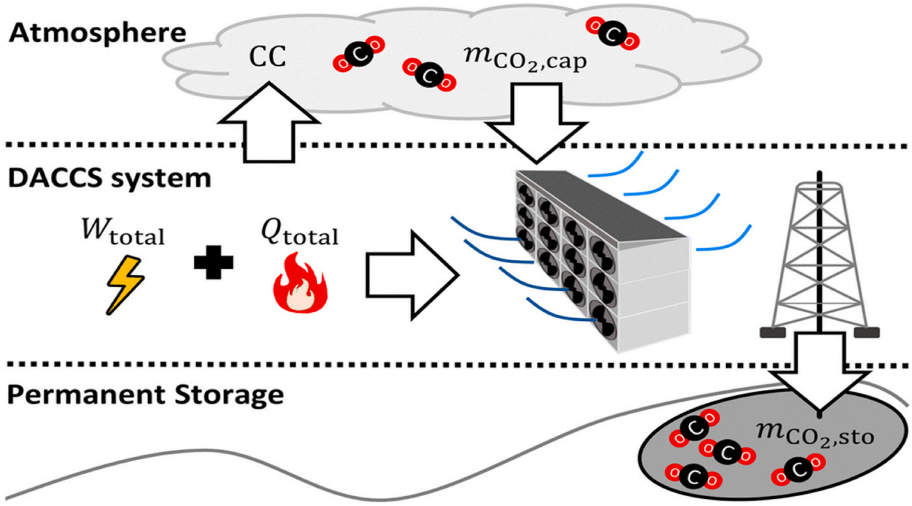

Fig. 12. Simplified visualization of the captured CO_2 mass (m_{co2},cap) and the GHGs emitted (CC) between the atmosphere, the DACCS system, and the permanent storage (m_{co2},sto) (Postweiler et al., 2024).

government to reduce by ~ 50 % of the economy-wide greenhouse gas emissions pollution from 2005 to 2030 with funds allocation of $12.1 billion for the development of Carbon capture, utilization, and storage (CCUS) technologies and projects through the infrastructure investment, availability of the expanded tax credits (45 Q credits) to defray the cost of CCUS projects and increasing net-zero emissions commitments from numerous companies have led to strong interest in CCUS in the 20-state region across the Midwest, mid-Atlantic and New England regions.

5.1.8. *Potential for collaboration between CVU and CURC*

While their geographical and industry focus areas differ, there's potential for future collaboration between CVE and CURC. They share a common goal of advancing CCU technologies, and information exchange or joint research projects could be beneficial.

The possible areas for Collaboration.

- Sharing best practices and technical knowledge in CCU technologies in specific areas of research findings, pilots and demonstration projects, technology road mapping, policy and regulatory frameworks, and market analysis with benefits of accelerated technological advancement, risk mitigation, overcoming technical barriers, standardization and interoperability, policy influence, talent development, and global leadership.
- Collaborating on advocacy efforts to promote supportive policies for CCU development with expanded reach, leveraging complementary strengths in terms of industry insights and research expertise, stakeholder engagement, and driving innovation, creating new market opportunities.
- Highlighting successful CCU projects globally to accelerate adoption will demonstrate the feasibility and commercial viability, inspiring innovation, attracting investors, building partnerships and addressing public concerns through joint publications and reports, organizing conferences and workshops, creating an online database, and establishing award and recognition for outstanding CCU projects.

Both CO_2 Value Europe and the Carbon Utilization Research Council are crucial in driving CCU innovation and implementation. Their work paves the way for a future with reduced reliance on fossil fuels and a more sustainable carbon cycle.

5.2. *Success stories in various industries: energy, manufacturing, agriculture, transportation*

CCUS has the goal to capture carbon dioxide, store it underground, or repurpose it for wide application in various industries to reduce the carbon footprint to 15–20 % by 2050 (see Fig. 13). The success stories in these industries are discussed below.

5.2.1. *Success stories in energy industries*

The energy industry embraces carbon capture, utilization, and storage (CCUS) technologies to tackle climate change. We have 3 success stories showcasing how CO_2 is being harnessed for sustainable solutions.

1 Enhanced Oil Recovery in the Permian Basin, USA:

Challenge: The Permian Basin, a prolific oilfield in the US, emits significant CO_2 into the atmosphere during extraction, processing, production, and transportation with a substantial footprint with critical climatic changes through energy consumption, transportation, flaring, and venting (Dismukes et al., 2019).

Solution: Exxon Mobil captures 120 million metric tonnes of CO_2 per year from its operations. This is equivalent to 40 % of the total anthropogenic CO_2 ever recorded to be captured through the purchase of the largest network in the US with more than 1500 owned and operated CO_2 pipelines and access to more than 15 onshore sites as CO_2 storage facilities. This captured CO_2 is then injected back underground to increase oil production through a process called Enhanced Oil Recovery (EOR) (Rassenfoss, 2022).

EOR utilizes CO_2 to displace remaining oil in the reservoir, effectively extending the well's life and maximizing resource recovery.

Impact: This project demonstrates the viability of CCUS for both economic benefit (increased oil production) and environmental improvement (reduced CO_2 emissions) (Rassenfoss, 2022).

2 **CarbonCure Technologies** - Converting CO_2 into Concrete Strengthener (Guo et al., 2024):

Challenge: The cement industry is a major contributor to global CO_2 emissions because cement is an essential component of concrete and the backbone of modern construction with ubiquitous applications from skyscrapers to roads. This is due to the energy-intensive from fossil fuel, staggering global demand with billions of tonnes produced.

Solution: CarbonCure Technologies developed a method to integrate captured CO_2 directly into concrete during mixing. The CO_2 chemically reacts to form stronger, more durable concrete.

Impact: This technology offers a double benefit: reducing CO_2 emissions by permanently storing it in concrete and creating a superior building material. CarbonCure estimates its technology has utilized over

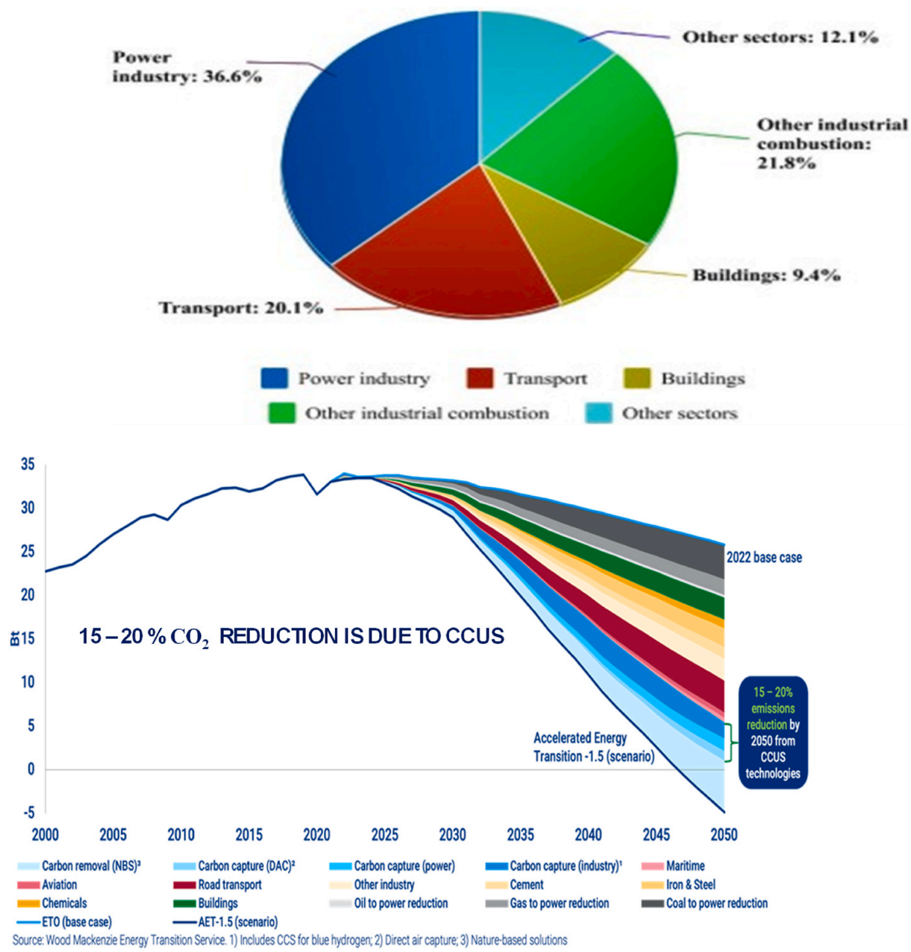

Fig. 13. The Industrial impact and goal of CCUS.

half a million tons of CO_2 to date.

3 **Iceland's Hellisheidi CarbFix Project** (Ragnheidardottir et al., 2011; Sigfú et al., 2018):

Challenge: Iceland stands as a global beacon for renewable energy with geothermal power forming the backbone of its energy infrastructure to achieve a near carbon neutral status, which can release CO_2 as a byproduct. Though the lower than the fossil fuel emissions but they can still contribute to climatic changes. Also, geothermal fluids has varied compositions with higher level of dissolved gas including CO_2.

Solution: The Hellisheidi CarbFix project captures CO_2 emissions from a geothermal power plant. The CO_2 is then dissolved in water and injected deep underground, where it mineralizes into rock formations over time.

Impact: CarbFix provides a safe and permanent storage solution for captured CO_2, preventing its release into the atmosphere. This is a crucial step for geothermal energy to become a truly sustainable power source.

These success stories showcase the potential of CCUS technologies to play a significant role in the energy transition. By harnessing CO_2, we can create a cleaner future while ensuring energy security and economic growth.

5.2.2. *Success stories in manufacturing industries*

Carbon dioxide (CO_2), the villain of climate change, is getting a makeover in the manufacturing industry. We have 3 success stories that showcase how companies are harnessing CO_2 to create sustainable solutions.

1 LanzaTech: Turning Emissions into Sustainable Fuels and Chemicals

Challenge: The conventional method stores the captured CO_2 underground but does not eliminate it because there are concerns such as leakage of CO_2 from the underground storage sites, and continuous monitoring of the storage sites to detect potential risks which is cost and resource-intensive, limited suitable underground storage sites and public perception on the safety and long-term implication (Brethauer and Studer, 2021).

Solution: LanzaTech, a New Zealand-based company, has developed a pioneering technology that utilizes captured industrial CO_2 emissions. Their unique microbes convert the CO_2 into ethanol, a versatile biofuel. This ethanol can then be further processed into chemicals used in everyday products like plastics and clothing (Brethauer and Studer, 2021).

Impact: LanzaTech partners with various industries, including steel and chemical production, to capture their CO_2 emissions and create a valuable resource. This not only reduces their environmental footprint but also creates new revenue streams (Brethauer and Studer, 2021).

2 CarbonCure Technologies: Trapping Carbon in Concrete

Challenge: The chemical reaction of calcining limestone during concrete formation produces carbon dioxide, increasing greenhouse gas emissions into the atmosphere. During carbonation, the concrete hardens by absorbing carbon dioxide from air, but the amount of carbon captured is significantly less than that released during cement production. The concrete industry is responsible for approximately 5–8 % of global Carbon dioxide emissions (Han et al., 2024).

Solution: Canadian company CarbonCure Technologies offers a revolutionary approach to the construction industry. Their technology injects captured CO_2 directly into concrete during the mixing process. Through a mineralization process, the CO_2 chemically reacts with the concrete, permanently trapping it within the structure (Ashirov and Coskun, 2024).

Impact: This not only reduces CO_2 emissions but also strengthens the concrete, leading to longer-lasting and more durable buildings. CarbonCure's innovation is being adopted by major construction companies worldwide, potentially significantly reducing the industry's carbon footprint (Ashirov and Coskun, 2024).

3 Covestro: Creating Sustainable Polyols with CO_2

Challenge: The plastic industry depends heavily on fossil fuels for raw materials which leads to 1) the Depletion of fossil fuels which is unsustainable, and 2) the release of greenhouse gases. Fossil fuels include oil, natural gas, and coal are finite resource formed over millions of years. Their extraction and processing for plastics production contributes to rapid depletion. This unsustainable consumption rate results in a global crisis that accelerates the need for an alternate, less scarce energy resource because as the fossil fuel reserve dwindles, their costs rise potentially influencing plastic production costs and the overall economy. The plastics industry's fossil fuel dependence is a double-edged sword cutting into resource sustainability and environmental health (Mneimneh et al., 2024).

Solution: German chemical giant Covestro has developed a process to utilize CO_2 in the production of polyols, a key component in the manufacturing of polyurethane foams. Traditionally, polyol production relies on fossil fuels. Covestro's technology captures CO_2 emissions and converts them into a sustainable alternative raw material (Zhu, 2019).

Impact: This not only reduces their reliance on fossil fuels but also creates high-performance polyols with similar properties to their conventional counterparts. Covestro's innovation paves the way for a more sustainable future for the polyurethane foam industry, used in everything from insulation to mattresses (Zhu, 2019).

5.2.3. Success stories in agriculture industries

Combating climate change requires innovative solutions, and agriculture is no exception. There are 3 success stories showcasing how farms are harnessing carbon dioxide (CO_2) to achieve a more sustainable future.

1 CO_2-Enriched Greenhouses for Booming Plant Growth:

Challenge: Traditional greenhouses often require significant energy for heating, especially in colder climates. This depends on 3 factors 1) large surface area: greenhouse expose a vast area to the environment leading to significant heat loss 2) Material conductivity: Many greenhouse materials allow light penetration and conduct heat accelerating energy dissipation. 3) Temperature fluctuation: Rapid temperature change between day and night that leads to constant heating adjustment (Ahamed et al., 2019).

The Solution: Several greenhouse operations are utilizing captured CO_2 from industrial facilities. By pumping this CO_2 into greenhouses, they create a CO_2-enriched atmosphere. Plants thrive in slightly elevated CO_2 levels, leading to increased growth rates and yields. This reduces the need for artificial heating, lowers energy consumption, and even improves the quality of some crops like tomatoes and peppers (De Gelder et al., 2012).

Success Story: E. J. Bakker, a Dutch tomato grower, has successfully implemented CO_2 enrichment in their greenhouses. They report a 20% increase in tomato yield while reducing their natural gas consumption by 15% (De Gelder et al., 2012).

2 Algae Farming: Transforming CO_2 into Biofuel and Animal Feed:

The Challenge: Livestock production generates significant methane emissions, a potent greenhouse gas. Additionally, traditional biofuel production can compete with food crops for land (Garnett, 2009). Global demand for meat and dairy products has led to the expansion of livestock farming. Livestock, particularly, ruminants like cattle and sheep produce significant amount of methane as a by-product of their digestive process. Methane is a potent greenhouse gas with far greater warming impact in a shorter timeframe. This has an environmental impact that contribute to climate change, impact to human health, and the ecosystem.

The push for renewable energy has led to an increase in biofuels obtained from agricultural crops but large-scale production of biofuel crops competes with food production for land, water, and other resources which leads to high food prices, especially staple crops, and leads to high food prices. It also leads to deforestation, soil erosion, and water pollution.

The Solution: Algae farming offers a double win. Algae can be grown in large tanks or ponds, utilizing captured CO_2 as a nutrient source. This captured carbon can then be converted into biofuels, reducing reliance on fossil fuels. Additionally, certain algae strains can be processed into protein-rich animal feed, offering a sustainable alternative to traditional sources like soy (Sarwer et al., 2022).

Success Story: Blue River Technology, a US-based company, has developed large-scale algae production facilities that capture CO_2 from industrial sources. The company refines the algae into biofuel and animal feed products (Mahmood et al., 2023).

3 Regenerative Agriculture: Building Soil Carbon for a Healthier Planet:

The Challenge: Conventional agricultural practices like frequent tillage, monocropping, excessive use of fertilizer, and residue removal often deplete soil organic carbon, a crucial component for healthy soil and plant growth. This loss also contributes to atmospheric CO_2 levels (Stockmann et al., 2013). The soil organic carbon (SOC) is a mixture of organic compounds that accumulates in the soil over time through the decomposition of animal and plant matters. The SOC is pivotal in building stable soil structure, reservoir for nutrient recycling like nitrogen and phosphorus, enhance water retention capacity and carbon sequestration. This loss of SOC also reduces agricultural productivity, accelerated climatic change and causing water pollution.

The Solution: Regenerative agriculture focuses on building soil health through practices like cover cropping, reduced tillage, and compost application. These practices promote the growth of beneficial soil microbes that capture carbon from the atmosphere and store it in the soil. This improves soil fertility, water retention, and crop yields while also mitigating climate change (Pontius and McIntosh, 2024).

Success Story: The Rodale Institute, a non-profit research organization, has been demonstrating the benefits of regenerative agriculture for decades. Their long-term studies show significant increases in soil organic carbon content on their research farms, leading to improved soil health and productivity (Kassam and Kassam, 2021).

5.2.4. Success stories in transportation industries

Transportation is a major contributor to greenhouse gas emissions. However, several innovative companies are using captured carbon dioxide (CO_2) to create sustainable solutions within this sector. 3 success stories.

1 **Electrofuels for Greener Shipping**:

Challenge: The traditional shipping industry relies heavily on fossil fuels. Global shipping in international trade is responsible for the movement of 90 % of world goods which traditionally releases significant amounts of greenhouse gases (CO_2) that influence climate change by global warming. The sheer size of the shipping industry magnifies its impact with billions of tons of cargo moved annually, the cumulative emissions are substantial with a disproportionate effect on the climate change. The increased CO_2 levels contribute to rising global temperatures, ocean acidification, and extreme weather events. These changes pose risks to coastal communities, marine ecosystems, and global food security. It is imperative to address the shipping industry's carbon footprint to mitigate climate change (Shenkin, 2023; Islam Rony et al., 2023).

Solution: Using synthetic fuel from renewable electricity and capturing carbon dioxide (Eze Ekechukwu et al., 2024).

Impact: Airbus is working on a revolutionary project that captures CO_2 emissions from power plants and industrial facilities. This captured CO_2 is then converted into electrofuels-clean, synthetic fuels that can be used by ships. This technology has the potential to significantly reduce emissions from the shipping sector (Murphy, 2024; Oke et al., 2024).

2 **E-fuels for Cleaner Aviation**:

Challenge: Long-haul flights use mostly fossil fuel-driven jets which increases greenhouse gas emissions during combustion. The battery technology, despite its advancement, has insufficient energy density to propel aircraft for the long journey while biofuel (an alternative fuel) has limited available sustainable biomass. Large-scale cultivation of biofuel could compete with food production and lead to deforestation, undermining the sustainability option (Cardone et al., 2023; Amhamed et al., 2024).

Solution: Creation of synthetic fuels from renewable electricity to drive electric or hybrid aircraft to decarbonize aviation and achieve net-zero emissions with high density and drop-in-compatibility infrastructure similar to conventional jets (Watson et al., 2024).

Impact: Air travel is another significant contributor to greenhouse gas emissions. Sunfire is a company that utilizes captured CO_2 and renewable electricity to produce synthetic fuels for airplanes. These e-fuels (electrofuels) can be used in existing aircraft engines, reducing reliance on traditional jet fuel and lowering the aviation industry's carbon footprint (Seymour et al., 2024).

5.3. Lessons learned and best practices for scaling up CO_2 conversion technologies

5.3.1. Lessons learned from scaling CO_2 conversion technologies

- **Lab to Life Gap**: Promising lab results often underestimate the challenges of large-scale implementation. Be prepared for unexpected engineering hurdles, especially the discrepancies between the controlled experimental conditions and complexities of real-world operations.
- **Cost Matters**: Early adopters may pay a premium but focus on driving down costs to achieve widespread adoption. This is due to high research and developmental costs, limited economies of scale (market penetration), and technological immaturity. It is also important to recognize that policy support from the government and securing stable, and affordable raw materials reduces the cost.
- **Energy consumption**: Some technologies require significant energy input. This is because different CO_2 technologies require different energy requirements. Understanding the energy profile of each technology is critical to its optimization of energy utility and efficiency. Prioritize renewable energy integration like solar, wind, and hydropower to maintain sustainability. To ensure a consistent energy supply for CO_2 conversion, especially in regions with intermittent renewable energy sources, energy storage technologies like batteries or hydrogen storage can play a vital role. This helps bridge the gap between renewable energy generation and energy demand for the conversion process.
- **Feedstock Focus**: Consider the source of CO_2 Capturing emissions from industrial sources is easier than extracting from dilute air because they have higher concentrations of CO_2, established infrastructures, and are economically viable. The implication is that scaling has lower costs, proven technologies, and faster deployment.
- **Product Pitfalls**: There is the need to carefully assess the market demand and environmental impact of the converted product. The market demand must be understood especially the market growth and size of the converted product. This has to be compared with the competitive landscape of existing products, their market share, and their pricing strategies with the potential of discovering their potential market gaps and opportunities. Conducting market research to determine customers' preferences and perceptions towards sustainability and willingness to pay a premium fee for eco-friendly products will provide a value sight.
- **Policy Push**: Government incentives and regulations can accelerate adoption and create a stable market by offering tax credits, grants, and subsidies. These financial incentives reduce upfront costs and risk, encouraging companies to develop and deploy new technologies. They can also provide loan guarantees which can lower the cost of capital for CO2 conversion projects, making them more financially attractive. The government can further provide regulatory frameworks to create a level playing field by creating carbon pricing and clear performance standards which create market value and push the boundaries of innovations for CO_2 emissions. Finally, the government should provide a stable environmental policy in terms of long-term commitment, and aligning policies across different levels of government (federal, state, local) can streamline the permitting and regulatory processes, reducing project timelines and costs for example The Inflation Reduction Act of 2022 given by the United States provide substantial tax credits for carbon capture, utilization, and storage (CCUS) projects, as well as for clean hydrogen production (Lin and Xu, 2024).
- **Lifecycle Analysis**: Consider the entire lifecycle of the technology, including energy use, material sourcing, and potential environmental risks. Conducting comprehensive LCAs for CO_2 conversion technologies is complex and requires data-intensive assessments. Challenges include data availability, methodological uncertainties, and the dynamic nature of the technologies. Despite these challenges, LCA offers valuable insights for improving the environmental performance of CO_2 conversion technologies. By identifying hotspots and areas for improvement, researchers and industry can develop more sustainable solutions. Additionally, LCA can help inform policy decisions and support the transition to a low-carbon future.
- **Public Perception**: Engage with communities and address concerns about safety and potential environmental consequences. There is need for early and continuous Engagement to build trust. You must engage in active listening: Understand local concerns, values, and priorities. There is need for shared decision-making: Involve the community in the decision-making process whenever possible. Be ready to address Safety Concerns: This involves risk assessment, emergency preparedness and being transparency: Be open about potential risks and mitigation measures. There is also skill to Mitigating Environmental concerns which involves life cycle analysis and sustainable practices as well as biodiversity conservation: Develop strategies to protect local ecosystems. Finally, education and awareness: through the use simple and understandable language to explain the technology.

Offering educational programs for the community and highlight the potential economic and environmental benefits.

- **Collaboration is Key**: Breakthroughs often come from interdisciplinary teams and partnerships between researchers, engineers, and industry. Researchers bring complementary skills through knowledge sharing to overcome the complex problems of converting CO_2 to valuable products require expertise in chemistry, material science, process design, and engineering to tackle the multifaceted problems. This will also include pooling resources in terms of funding, facilities, and equipment, to amplify the impact of the research efforts and accelerate the time to the market by efficient development of the process and industry alignment. They can also build a strong ecosystem of knowledge transfer and policy influence on CO_2 conversion.

5.3.2. Best practices for scaling CO_2 conversion technologies

- **Modular Design**: Break down the technology into smaller, replicable units for easier construction and deployment. The CO_2 conversion technologies have to be divided into standard, independent modules that can be produced, assembled, and operated separately. Mass production of the standard modules leads to cost efficiency in economies of scale. This makes it easier for replacement, upgrading, or reconfiguring to adapt to changing technologies or conditions and prevent risks.
- **Life Cycle Optimization**: Optimize for energy efficiency, minimize waste generation, and choose sustainable materials. The optimization of energy efficiency includes process optimization by identifying and eliminating the energy-intensive steps in the CO_2 process conversion. It is energy recovery by the reuse and capture of waste heat as well as the use of renewable energy integration to avoid carbon footprint. The waste minimization involves the process design to generate minimal waste products, convert the waste streams to valuable products or energy sources, and implement the loop system to recycle the materials and reduce waste disposal. The sustainability of the process involves the evaluation of the environmental impact of materials used in the conversion process which prioritize materials with low carbon footprints. Incorporate recycled materials whenever possible. It is crucial to conduct thorough environmental impact assessments to identify potential risks and mitigation strategies and evaluate the economic viability of life cycle optimization measures, considering costs and benefits.
- **Standardization**: Develop industry standards for performance, safety, and data collection to facilitate wider adoption. The performance metrics are required for standardization by establishing clear and consistent metrics to measure the efficiency, productivity, and overall performance of CO_2 conversion systems. These parameters include conversion rates, product yield, energy consumption, and carbon capture efficiency. Create tools to compare different technologies' performance and identify improvement areas. This will help drive innovation and optimize system designs. As part of safety standards, it is important to establish comprehensive safety guidelines for the handling, transportation, and conversion of CO_2 and for the operation and maintenance of CO_2 conversion facilities. Implement risk assessment procedures and ensure operator's training and certifications. It is also important to define standards for collection, sharing, promoting, management and analyzing of data. This will facilitate the development of technology, boost of investors' confidence, integrated into various applications, expand market opportunities improved environmental performance, and enhance public acceptance.
- **Life Cycle Assessment**: Conduct thorough Life Cycle Assessments to identify areas for improvement and communicate environmental benefits.

The LCA should cover the entire lifecycle of the technology, from raw material extraction to product end-of-life. Accurate and reliable data is essential for accurate results. Data should be sourced from credible and peer-reviewed studies. Choose appropriate impact assessment methods that align with the goals of the LCA. Common methods include CML-IA, ReCiPe, and EDIP. Assess the impact of uncertainties in data and assumptions on the LCA results. Compare the LCA results of different CO_2 conversion technologies to identify the most environmentally beneficial options. Identifying Areas for Improvement such as stages in the process with high energy consumption and exploring opportunities for energy efficiency improvements, minimizing the use of non-renewable resources and identifying opportunities for material recycling or reuse, reducing waste generation through process optimization and exploring opportunities for waste valorization and focus on reducing negative environmental impacts, such as greenhouse gas emissions, water consumption, and land use.

- **Open Innovation**: Encourage open-source collaboration and knowledge sharing to accelerate technological advancements. Create platforms and communities where researchers, industry experts, and policymakers can exchange ideas, share data, and collaborate on projects. Implement reward systems or grants for researchers and companies that openly share their findings and innovations. Establish clear IP guidelines to encourage innovation while safeguarding proprietary information. Consider open-sourcing non-core technologies to promote wider adoption. Utilize existing open-source tools and software to accelerate development and reduce costs.
- **Pilot Projects**: Demonstrate the technology's viability through well-designed pilot projects that gather real-world data. Choose a technology aligned with specific CO2 sources and desired product outputs. Consider factors like CO2 availability, infrastructure, and regulatory environment. Develop a comprehensive plan addressing feedstock, process parameters, product characterization, and environmental impact assessment. Implement robust monitoring and data management systems to capture critical performance indicators. Engage with stakeholders, including industry experts, policymakers, and local communities. Continuously analyze the project's potential for scaling, identifying bottlenecks and optimization opportunities.
- **Cost Reduction Strategies**: Identify areas for cost reduction throughout the supply chain and explore innovative financing models. This involves 3 main methods-

1) Process Optimization by optimizing energy consumption in the conversion process through advanced process control, heat integration, and energy recovery systems, investing in research and development to create more efficient and durable catalysts, reducing replacement costs, and improving conversion rates as well as optimizing reactor design for maximum efficiency and product yield, minimizing energy input and raw material consumption. 2) Supply Chain Optimization by exploring low-cost CO_2 capture technologies and sources, such as industrial emissions or direct air capture with reduced energy requirements, securing stable and cost-effective supply chains for additional raw materials required in the conversion process, optimizing transportation logistics to minimize costs and emissions, considering factors like proximity of CO_2 sources and product markets. 3) Product Development and Market Expansion by developing a range of high-value products to increase revenue and reduce reliance on a single market. Identify and target high-growth markets with strong demand for CO_2-derived products. Improve product quality and performance to enhance market competitiveness. Innovative Financing Models should be employed which include: Collaboration with governments, research institutions, and private investors to share risks and costs. Utilization of carbon markets to generate additional revenue by selling carbon credits associated with CO_2 conversion projects. Technology Licensing and Royalty Agreements with other companies to generate revenue and accelerate market penetration. Attract (Placeholder2) investment from venture capital firms and impact investors focused on sustainable technologies. Leverage tax credits, grants, and subsidies offered by governments to support CO_2 conversion projects.

6. Challenges and future directions

Investigating CO_2 capture and conversion technologies has intriguing prospects for turning greenhouse gas emissions into profitable resources. Such technologies mark a turning point in sustainability, generating revenue while mitigating environmental effects. Nevertheless, significant technological, regulatory, social, and economic hurdles must be overcome to reach the full potential of CO_2 mitigation technologies. This section delves further into these challenges and provides future directions for study, development, and policy. By addressing these issues, the shift to a circular carbon economy may be promoted by encouraging innovation. As a result, this broad strategy benefits the environment and promotes global sustainable development objectives (SDGs).

6.1. Technical challenges: efficiency, scalability, cost-effectiveness

Significant technical challenges impede the efficiency, scalability, and cost-effectiveness of CO_2 capture and conversion technologies, hindering their broader implementation.

6.1.1. Efficiency

A diverse array of carbon capture and conversion technologies are available. Fig. 14 shows an overview of these distinct approaches, emphasizing their varied paths and interactions. The energy-intensive nature of these processes is one of the most pressing issues. In fact, the many required energy-intensive phases, such as compression, transportation, and storage, add to the total energy and cost burden (Bui et al., 2018). For instance, amine-based absorption, despite being one of the most established capture technologies, requires high energy input due to the endothermic nature of solvent regeneration and the degradation of amines over numerous cycles, leading not only to lower capture efficiency over time but also to increase operational costs due to solvent degradation, replacement, and disposal (Li et al., 2013). Moreover, converting captured CO_2 into value-added products such as hydrocarbons, chemicals, or polymers poses its own set of efficiency issues. Catalytic reactions, which are critical to CO2 conversion, often require severe reaction conditions (e.g., high pressures and temperatures) and rely on expensive and scarce catalysts, such as noble metals (Kanjilal et al., 2020).

Similarly, the energy-intensive process of mixing and maintaining optimal conditions for algae growth depletes the total CO_2 balance in the case of biological conversion processes (Goli et al., 2016). Thereby, defeating the aim of CO_2 mitigation. Along with that, environmental constraints such as temperature fluctuations, light intensity, and hazardous gases presence such as nitrogen and sulfur impede these biological processes' scalability (Lam et al., 2012). To address these issues, several sophisticated CO_2 capture systems have been investigated, including adsorption using solid materials such as activated carbon and metal-organic frameworks (MOFs), cryogenic separation, and chemical looping (Kanjilal et al., 2020). However, these technologies also face significant hurdles. For instance, adsorption processes are limited by low CO_2 selectivity, moisture sensitivity, and adsorbent regeneration, which decrease their efficiency and increase operational costs (Bamdad et al., 2018). Cryogenic techniques can provide high CO_2 recovery and purity, but it poses significant obstacles due to the energy-intensive cooling process and the need for sophisticated cryogenic storage systems (Tuinier et al., 2010). Additionally, Impurities in the CO_2 stream, such as water and sulfur compounds, can further complicate cryogenic separation and raise operating costs (Kanjilal et al., 2020). Meanwhile, to enhance oxidation and reduction processes, chemical looping involves using solid oxygen carriers, usually transition metal oxides (Solunke and Veser, 2011). Despite its promise, it stills in its early stages due to ongoing major roadblocks like insufficient oxygen supply and sulfur contamination (Kanjilal et al., 2020).

6.1.2. Scalability

Scalability is another major challenge for CO_2 capture and conversion methods. The major constraint lies in bridging the gap between laboratory-scale success and industrial-scale efficiency. In research, there is often a tendency to idealize and overestimate the performances of new and innovative technologies, making unrealistically confident promises about scalability. However, without thorough valuation of potential limitations, these promises would fall by the wayside on the

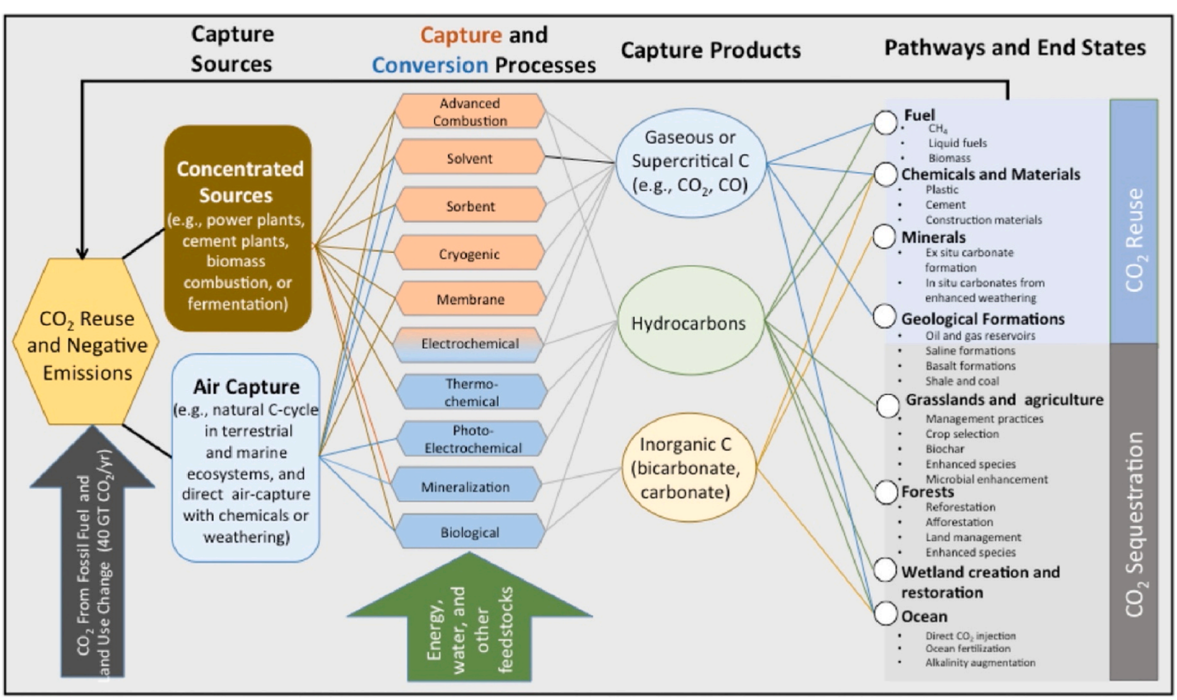

Fig. 14. A broad depiction of the various technologies and processes involved in carbon capture, conversion, sequestration, and reuse aimed at achieving net-zero or negative emissions (Deutch, 2016).

industrial scale (Chkirida et al., 2022).

Implementing large-scale CO_2 capture infrastructure, such as capture units, transportation systems, and storage or usage facilities, requires a substantial capital investment (Kanjilal et al., 2020). Scaling-up cryogenic capture technologies, for example, requires complicated and energy-intensive cooling energy systems that may not be practicable at a wider scale (Kanjilal et al., 2020). Likewise, membrane separation methods, although straightforward and environmentally friendly, are subject to fouling and wetting, quire multistage flux recycling to enable effective removal at higher sizes, complicating their expansion (Sreedhar et al., 2017).

Furthermore, the integration of CO_2 capture technology into current industrial processes, such as chemical manufacturing, cement manufacture, or power generation, necessitates considerable facility upgrading. These retrofitting efforts must guarantee that CO_2 capture technologies are integrated without interrupting current operations, which add complexity and cost to scaling (Koytsoumpa et al., 2016).

Technologies for CO_2 conversion have similarly difficult scaling issues. Industrial-scale CO_2 conversion into fuels and chemicals, such as methanol or synthetic fuels, requires not only the availability of CO_2 feedstocks but also consistent product quality across all sizes (Kanjilal et al., 2020). The economic incentives to scale these conversion technologies remain restricted in the absence of a clear market demand and a reliable infrastructure for feedstock supply and product delivery (Koytsoumpa et al., 2016). As a prime example, industrial-scale methanol synthesis from CO_2 and hydrogen has demonstrated promising conversion efficiencies surpassing 60%. Nonetheless, the process is heavily energy-consuming, requiring 0.15 MWhe of electricity per ton of methanol produced, for a total electrical energy consumption of 9.89 MWhe per ton (Buddenberg et al., 2016). Subsequently, widespread adoption of such methods is challenging since their economic feasibility is heavily reliant on market conditions, such as changing regulatory regimes and methanol pricing (Koytsoumpa et al., 2016). Furthermore, a lack of infrastructure for hydrogen generation, storage, and transportation significantly limits the scalability of CO_2 usage methods (Koytsoumpa et al., 2018). The integration of renewable energy sources, such as wind and solar, into these processes could enhance their sustainability, but the intermittency and reliability of these energy sources pose additional technical challenges.

6.1.3. Cost-effectiveness

Arguably, the biggest obstacle to the broad adoption of CO_2 capture and conversion technology is their cost-effectiveness. When compared to the pricing of fossil-fuel-derived products, the economic viability of CO_2 conversion technologies is seriously questioned. For instance, it is currently more costly to produce synthetic fuels from CO_2 using Fischer-Tropsch synthesis or electrochemical reduction than refining fossil fuels using conventional approaches (Fasihi et al., 2019). In fact, Direct air capture (DAC) costs have been frequently estimated in the literature, spanning \$20 to \$1000 per ton of CO_2 (Ozkan, 2024b). Though they indicate that initial expenses for pioneering facilities might be as high as \$600–\$1000 per ton, S. Fuss (Fuss et al., 2018) narrow this range to \$100–\$300 per ton of CO_2. The cost gap is mostly due to the demanding energy needs and the cost of electricity or catalysts used in the conversion processes. Further economic difficulties are brought on by the availability and price instability of hydrogen, a crucial component in many CO_2 conversion processes. Addressing these difficulties will need ongoing advances in materials science, process engineering, and energy optimization, as well as supporting regulatory frameworks that encourage the development and deployment of new technologies.

6.2. Regulatory and policy barriers: Carbon pricing, incentives for CO_2 utilization

The regulatory landscape for CO_2 capture and conversion technologies, like many other technological innovations is complicated due to major regulatory and policy barriers. These policies are often inconsistent across regions, posing substantial impediments to a wider adoption despite the CO_2 significant technological advancements (Cabrera et al., 2022). The low commercial of success of these techniques is mostly due the lack of a comprehensive and unified regulatory framework tailored to meet the demands of CO_2 capture and conversion. In fact, the majority of current policies predominantly address emissions reduction and carbon price, without adequately taking into account the complexities involved in CO_2 capture and conversion processes or the safe use of CO_2-derived products. For stakeholders, this regulatory gap creates a great deal of ambiguity, discouraging investment and restricting the rate of innovation in this industry (Olfe-Krä et al., 2021). The policy barriers are divided into three main groups: early development support, incentives, and guidance for deployment and market regulation. Governments and funding agencies frequently handle technological innovation via "technology-push" or "market-pull" techniques (Horbach et al., 2012).

Technology-push policies aim to promote technology advancement by providing funds and other forms of incentives to support research, demonstration projects, and early-stage implementation (Olfe-Krä et al., 2021). These policies have been critical in accelerating the development of CO_2 mineralization technology. As an example, Canada's Boundary Dam Carbon Capture Project benefited from government backing as part of Canada's implementation of international climate agreements (Stéphenne, 2014). Early-stage assistance is crucial, as demonstrated by the project's successful integration of carbon capture with a coal-fired power station. However, this also underlines the challenges of high costs and the necessity for important legislative backing to permit scaling-up.

On 2the other hand, *market-pull policies* seek to generate or expand market demand for products or servi2ces. These comprise market-based instruments (MBIs) like Emissions Trading Schemes (ETS), tax cr2edits, and subsidies, as well as command-and-control (CAC) measures that enforce regulatory instrum2ents and performance mandates with penalties for noncompliance (Olfe- Krä et al., 2021). Fig. 15 depicts the various c2arbon pricing established across regions and nations via taxes or cap-and-trade systems. This graph she2ds light on the present range of carbon pricing, demonstrating that the majority of rates are less than \$2225 per ton of CO_2. This variant emphasizes the difficulty of creating strong enough incentives to result in significant emissions reductions and the necessity of well-crafted market-based policies to drive demand for low-carbon products and technology successfully (Gür, 2022). The Climeworks Direct Air Capture project in Switzerland is an excellent illustration of how European climate policies, such as those linked with the EU Green Deal, have assisted in developing and implementing innovative carbon-reduction solutions (Sovacool et al., 2022). Despite the present high energy and cost needs of direct air capture technology, Switzerland's supportive governmental climate has enabled Climeworks to pioneer it.

Moving forward, there is an urgent need for policy intervention that should be dependable and continuous, guaranteeing an assessment of potential benefits to society and the environment, and supporting the sustainability of CO_2 mineralization technologies. Additionally, it is worthwhile to establish clear guidelines for the lifecycle assessment of CO_2-derived products, ensuring that they deliver net en2vironmental benefits, without contributing to other forms of pollution or resource depletion.

6.3. Public perception and acceptance: Environemental impact, safety concerns

The effective implementation of carbon capt22ure/conversion and utilization technology is contingent upon the perception and acceptance of the public. New energy solutions frequently encounter skepticism or outright rejection from the public2, despite these technologies' potential advantages. This covers a wide range of sustainable and renewabl22e

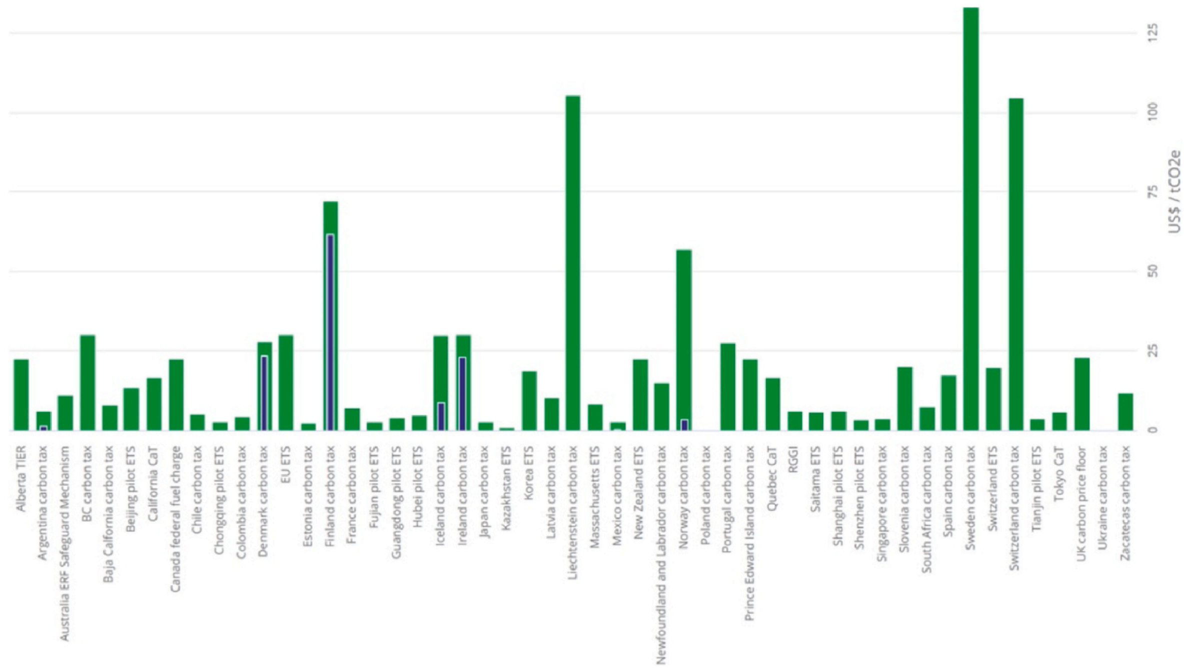

Fig. 15. Gl2obal carbon pricing initiatives, including carbon taxes and emissions trading schemes (ETS) or cap-2and-trade systems, show the implemented carbon prices. The vertical axis represents values in US2 dollars per ton of CO2 equivalent (US$/tCO2e). Reprinted with permission from 22Elsevier (Gür, 2022).

energy solutions, not only CO_2 technologies (Nielsen et al., 2022).

Public acceptance is influenced by a complex interplay of factors, yet there is no comprehensive psychological model that fully explains technology acceptance. To better explain public perception, attempts have been made by integrating many psychological theories, such as the theory of affect, of planned behavior, and of norm activation (L' et al., 2014). One such attempt is the framework developed by N. Huijts (Huijts et al., 2012). These perceptions are shaped by factors involving stakeholder trust, perceived potential hazards and benefits, and knowledge of the CO_2 technologies. Still, the general public's knowledge about these technologies remains low, affecting acceptance through misconceptions (L' et al., 2014). Knowledge plays an essential role in molding public view, as it greatly affects people's assessment of CO_2 technology and spans from mere awareness to both subjective and objective knowledge. Based on this framework, educational initiatives emphasizing the science underpinning CO_2 conversion and its potential to alleviate climate change can help shift public perception. Increased acceptability may also be fostered by including communities in decision-making processes and making sure that CO_2 use initiatives complement regional economic and environmental objectives. Future research should concentrate on understanding public perceptions toward CO_2-derived products and finding solutions to address concerns via transparent and inclusive engagement (Witte, 2021).

Given that people often rely on familiar concepts as reference points, comparisons to other technologies, such as fossil fuel extraction, are likely to impact people's perceptions. Additionally, public perceptions can be influenced by tangible encounters with related technologies, although direct experience with CO_2 capture and conversion is limited (L' et al., 2014). Another vital indicator of technological acceptance is stakeholder trust. In cases when information is lacking, people frequently rely on the credibility of promoters or opponents to determine if a technology is acceptable. In fact, transparent communication about the benefits and risks associated with CO_2 conversion are necessary to build public trust and support. Also, acceptance is highly influenced by the notion of distributive and procedural justice. The appropriate adoption of a technology, including the distribution of costs, risks, and benefits, can have a significant impact on public support (Witte, 2021). Attitude development is also influenced by emotional reactions to a technology. In fact, emotions, both good and bad, play different roles in how people see and accept things (Nielsen et al., 2022). Perceived dangers, such as those related to money, health, or safety, can also be obstacles to acceptance. The NIMBY (Not in My Backyard) effect (Arning et al., 2019), also diminishes the technology acceptability especially when people are directly impacted by it, such as living close to CO_2 capture/conversion facilities. While early research on CO_2 research reveals a generally positive impression of the technology, inquiries remain, notably about its long-term usefulness as a climate change mitigation strategy. Although the technology's long-term sustainability is still questioned, environmental advantages including reduced CO_2 emissions and the saving of fossil fuels are acknowledged.

6.4. *Research and development priorities: improving conversion efficiency, exploring novel applications*

Continuous research and development (R&D) activities are required to address the technological and socioeconomic concerns raised. One of the top priorities is creating next-generation catalysts and processes that operate well in mild environments while significantly reducing the energy requirements and expenses related to CO_2 conversion. Additionally, investigating novel applications for CO_2-derived products, such as in sustainable building materials and advanced polymers, may broaden the market and improve the economic viability of these technologies (Muthuraj and Mekonnen, 2018). The combination of high-efficiency materials with advanced computational methods seems a handy approach to lower prices and reducing energy consumption. Beyond merely improving the efficiency of materials and catalysts, engineering-level computation-based innovation provides a significant pathway to increasing the feasibility of large-scale CO_2 capture and conversion (Jerng et al., 2024). To establish a cost-effective CO_2 value chain, it is critical to evaluate the entire system holistically. Enhancements must involve the integration of upstream capture, logistics, and downstream conversion rather than concentrating solely on CO_2 capture and conversion. This calls for a cooperative strategy that shares and integrates computational data, both large and small, throughout the value chain. In fact, given the early stage of CO_2 utilization technologies, where pilot and demonstration plants are limited, computational strategies and instruments will be critical in speeding up the discovery, development, and deployment of materials and processes (Yuan et al., 2016). Another key priority is ensuring that the selection of materials for the CO_2 value chain emphasizes selectivity, stability, capacity, and impurity tolerance. Materials that excel in one feature but lack in others may be unsatisfactory for large-scale adoption. While current material discovery techniques often fail to identify materials with all of the intended target attributes, integrating experimental and computational screening at the microscale with system-level assessment is much needed for the discovery process (Yuan et al., 2016). Advances in computer science, mathematics, and high-throughput computational methodologies can facilitate the integration of macroscopic performance evaluation and microscopic screening within in silico hierarchical computational frameworks (First and Hasan, 2014). Nevertheless, experimental screening is still necessary to validate the discovered materials. Last but not least, research in materials science is of vital importance to come up with novel materials, including dual-function materials (DFMs), in order to overcome the drawbacks of current and conventional carbon capture and sequestration materials (Alami et al., 2020). Dual-function materials (DFMs) have emerged as a more plausible solution combining catalytic and adsorbent elements for CO_2 capture and conversion into value-added products in a single process (Omodolor et al., 2020). Typically, the adsorbent is made of alkali metal oxides or carbonates, which absorb CO_2 straight from flue gas. Using the catalytic component, captured CO_2 is converted into valuable products like hydrocarbons and chemicals. DFMs also efficiently concentrate CO_2 from dilute streams, thereby removing the need for standard procedures such as transportation and storage (Melo Bravo and Debecker, 2019).

6.5. Future outlook and potential for a circular carbon economy

A circular carbon economy, where CO_2 is continuously recycled and reused, holds immense potential in the future. To make this vision a reality, many key requirements and indications for creating and executing a reliable and optimum large-scale CO_2 value chain must be addressed.

- The process of CO_2 capture and conversion should be efficient enough to extract at least 90% of the gas from stationary sources while consuming the least amount of energy and power. Furthermore, the CO_2-derived products' energy content needs to be higher than the energy needed to produce them. Hence, the overall CO_2 value chain should ensure that the amount of CO_2 emitted is less than the total amount converted, enhancing the sustainability of the process (Yuan et al., 2016).
- The methods for CO_2 conversion and capture must exhibit both process flexibility and operational ease for a straightforward management. In addition, the CO_2 conversion process should be flexible enough to adjust to the variations in market demand and allow the production of multiple products, all while maintaining low capital costs and minimal environmental impacts (Yuan et al., 2016).
- Materials for CO_2 capture should be highly selective and productive, operate with minimal energy demands, maintain long-term stability, and demonstrate strong tolerance to contaminants and impurities. These materials synthesis and production processes need also to be scalable, economical, and environmentally benign to meet the demands of CO_2 capture and conversion technologies (Zanatta, 2023).
- Multidisciplinary efforts and coordinated approaches, encompassing basic scientific research, materials science, engineering innovations, policy-making, and environmental considerations across various scales and timeframes are worthwhile for the successful development and deployment of CO_2 capture and conversion technologies.
- The CO_2 conversion and capture systems have to be scalable and robust enough to maintain high performances even under changing circumstances. These systems should also be designed with scalability in mind, allowing for a seamless transition from pilot projects to full-scale industrial applications without compromising efficiency or raising costs (Dziejarski et al., 2023b).
- Comprehensive CO_2 capture studies should be conducted under conditions resembling industrial flue gas environments, such as high temperatures, low pressure, and changing moisture content. A variety of material configurations should be used in these tests to properly imitate and confirm performance in real-world applications.
- As much as CO_2 capture and conversion seems like a sustainable technique that fits the circular economy, it is crucial to make sure that the entire process is sustainable. Materials preparation, carbon capture technologies, and conversion processes being the specific instances. The overall environmental eco-friendliness of the valorization process, however, may be jeopardized in some cases of the overall process since it may make use of hazardous chemicals or need large energy inputs (Dziejarski et al., 2023b). Rigorous environmental impact assessments (EIA) and long-term monitoring are essential to ensure that these technologies provide net environmental benefits.
- Thorough guidelines and standardized protocols for CO_2 capture materials should be created, considering the most optimal possible process conditions in terms of temperature, pressure, gas concentration, and goal CO_2 purity. These protocols should also handle specific application circumstances, such as pre-combustion, post-combustion, and oxy-fuel combustion, as well as define textural property and overall performance standards (Dziejarski et al., 2023b).
- Environmental stewardship and social responsibility concepts should guide the development and implementation of CO_2 capture technology. This entails making certain that these technologies benefit communities and ecosystems without bringing out new environmental or social problems, such as pollution or resources depletion.

By addressing these critical factors, CO_2 can be transformed from a waste product into a valuable resource, driving sustainable development and significantly reducing the anthropogenic carbon footprint.

7. Conclusion

The review highlights several key findings and insights, emphasizing the potential of advanced technologies in transforming CO2 from a detrimental greenhouse gas into a valuable resource. These technological advancements offer significant implications for climate change mitigation by reducing atmospheric CO2 levels and promoting the development of sustainable energy sources. Furthermore, they present lucrative opportunities for wealth generation, turning environmental challenges into economic benefits. To capitalize on these opportunities, a collaborative approach is essential. Researchers, industry leaders, policymakers, and stakeholders must work together to accelerate the adoption of CO2 conversion technologies. This collaboration should focus on scaling up research, optimizing industrial applications, and creating supportive policy frameworks that incentivize innovation and investment in this field. Public-private partnerships and international cooperation can also play a pivotal role in overcoming technical and economic barriers, ensuring a smooth transition from CO2 waste to wealth. In conclusion, harnessing CO2 for a sustainable future holds transformative potential. By converting CO2 into valuable products, we can address climate change, enhance energy security, and stimulate economic growth. This dual benefit underscores the importance of continued research and innovation. As we move forward, it is imperative to foster an environment that encourages collaboration and investment in CO2 conversion technologies, paving the way for a greener and more prosperous future.

Funding

This research received no external funding.

CRediT authorship contribution statement

Yakubu Adekunle Alli: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Abayomi Bamisaye:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Formal analysis, Data curation. **Muyideen Olaitan Bamidele:** Writing – original draft, Visualization, Validation, Software, Methodology, Data curation. **Nelson Oshogwue Etafo:** Writing – original draft, Software, Project administration, Methodology, Formal analysis, Data curation. **Soulaima Chkirida:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Afolashade Lawal:** Writing – original draft, Visualization, Validation, Investigation, Data curation. **Victor Oluwafolajimi Hammed:** Visualization, Validation, Software, Investigation, Data curation. **Ayobami Samuel Akinfenwa:** Data curation, Formal analysis, Project administration, Visualization. **Enobong Hanson:** Validation, Software, Resources, Formal analysis, Data curation. **Chukwuebuka Nwakile:** Visualization, Validation, Software, Methodology. **Kolawole Osuolale Kazeem:** Writing – original draft, Investigation, Data curation. **Rebecca Juliet Ayanwunmi:** Data curation, Formal analysis, Validation. **Akinsanmi S. Ige:** Data curation, Software, Visualization. **Jose Refugio Parga Torres:** Validation, Project administration, Data curation. **Hassan Al Nageim:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

All authors acknowledge their universities for the enabling platform to carry out this research.

Data availability

No data was used for the research described in the article.

References

Abdel-Shafy, H.I., Ibrahim, A.M., Al-Sulaiman, A.M., Okasha, R.A., 2024. Landfill leachate: sources, nature, organic composition, and treatment: an environmental overview. Ain Shams Eng. J. 15, 102293. https://doi.org/10.1016/j.asej.2023.102293.

Ahamed, M.S., Guo, H., Tanino, K., 2019. Energy saving techniques for reducing the heating cost of conventional greenhouses. Biosyst. Eng. 178, 9–33. https://doi.org/10.1016/j.biosystemseng.2018.10.017.

Ahmad, A., Arif, M.S., Shahzad, S.M., Yasmeen, T., Shakoor, A., Iqbal, S., Riaz, A., Zahid, A., Chapman, S.J., 2024. Long-term raw crop residue but not burned residue incorporation improved soil multifunctionality in semi-arid agroecosystems. Soil Tillage Res. 240, 106073. https://doi.org/10.1016/j.still.2024.106073.

Ahmed, S.F., Mofijur, M., Nuzhat, S., Rafa, N., Musharrat, A., Lam, S.S., Boretti, A., 2022. Sustainable hydrogen production: technological advancements and economic analysis. Int. J. Hydrogen Energy 47, 37227–37255. https://doi.org/10.1016/j.ijhydene.2021.12.029.

Al Harthi, A., Al Abri, M., Younus, H.A., Al Hajri, R., 2024. Criteria and cutting-edge catalysts for CO_2 electrochemical reduction at the industrial scale. J. CO2 Util. 83, 102819. https://doi.org/10.1016/j.jcou.2024.102819.

Alami, A.H., Abu Hawili, A., Tawalbeh, M., Hasan, R., Al Mahmoud, L., Chibib, S., Mahmood, A., Aokal, K., Rattanapanya, P., 2020. Materials and logistics for carbon dioxide capture, storage and utilization. Sci. Total Environ. 717, 137221. https://doi.org/10.1016/j.scitotenv.2020.137221.

Ali, Q. ul A., Khayyam, U., Nazar, U., 2021. Energy production and CO2 emissions: the case of coal fired power plants under China Pakistan economic corridor. J. Clean. Prod. 281, 124974. https://doi.org/10.1016/j.jclepro.2020.124974.

Alsunousi, M., Kayabasi, E., 2024. The role of hydrogen in synthetic fuel production strategies. Int. J. Hydrogen Energy 54, 1169–1178. https://doi.org/10.1016/j.ijhydene.2023.11.359.

Amhamed, A.I., Al Assaf, A.H., Le Page, L.M., Alrebei, O.F., 2024. Alternative sustainable aviation fuel and energy (SAFE)- A Review with selected simulation cases of study. Energy Rep. 11, 3317–3344. https://doi.org/10.1016/j.egyr.2024.03.002.

Amoo, L.M., Layi Fagbenle, R., 2020. Climate change in developing nations of the world, Applications of Heat. Mass and Fluid Boundary Layers 437–471. https://doi.org/10.1016/B978-0-12-817949-9.00023-2.

Andika, R., Nandiyanto, A.B.D., Putra, Z.A., Bilad, M.R., Kim, Y., Yun, C.M., Lee, M., 2018. Co-electrolysis for power-to-methanol applications. Renew. Sustain. Energy Rev. 95, 227–241. https://doi.org/10.1016/J.RSER.2018.07.030.

Arias, A., Nika, C.-E., Vasilaki, V., Feijoo, G., Moreira, M.T., Katsou, E., 2024. Assessing the future prospects of emerging technologies for shipping and aviation biofuels: a critical review. Renew. Sustain. Energy Rev. 197, 114427. https://doi.org/10.1016/j.rser.2024.114427.

Arning, K., Offermann-van Heek, J., Linzenich, A., Kaetelhoen, A., Sternberg, A., Bardow, A., Ziefle, M., 2019. Same or different? Insights on public perception and acceptance of carbon capture and storage or utilization in Germany. Energy Pol. 125, 235–249. https://doi.org/10.1016/j.enpol.2018.10.039.

Arun, M., Barik, D., Chandran, S.S.R., 2024. Exploration of material recovery framework from waste – a revolutionary move towards clean environment. Chemical Engineering Journal Advances 18, 100589. https://doi.org/10.1016/j.ceja.2024.100589.

Ashirov, T., Coskun, A., 2024. Carbon dioxide capture: current status and future prospects. Chimia 78, 415–422. https://doi.org/10.2533/chimia.2024.415.

Avogadro, N., Redondi, R., 2024. Pathways toward sustainable aviation: analyzing emissions from air operations in Europe to support policy initiatives. Transp Res Part A Policy Pract 186, 104121. https://doi.org/10.1016/j.tra.2024.104121.

Ayeleru, O.O., Modekwe, H.U., Onisuru, O.R., Ohoro, C.R., Akinnawo, C.A., Olubambi, P. A., 2023. Adsorbent technologies and applications for carbon capture, and direct air capture in environmental perspective and sustainable climate action. Sustainable Chemistry for Climate Action 3, 100029. https://doi.org/10.1016/j.scca.2023.100029.

Azhar, U., Yaseen, S., Arif, M., Babar, M., Sagir, M., 2024. Chapter Seven - emission of greenhouse gases from transportation. In: M.R. Rahimpour, M.A. Makarem, M.B.T.-A. and T.D, Meshksar, G.G.E. (Eds.), Capture and Conversion. Elsevier, pp. 147–163. https://doi.org/10.1016/B978-0-443-19231-9.00016-8.

Aziz, S., Chowdhury, S.A., 2023. Analysis of agricultural greenhouse gas emissions using the STIRPAT model: a case study of Bangladesh. Environ. Dev. Sustain. 25, 3945–3965. https://doi.org/10.1007/s10668-022-02224-7.

Bailera, M., 2023. Comparing different syngas for blast furnace ironmaking by using the extended operating line methodology. Fuel 333, 126533. https://doi.org/10.1016/j.fuel.2022.126533.

Bamdad, H., Hawboldt, K., MacQuarrie, S., 2018. A review on common adsorbents for acid gases removal: focus on biochar. Renew. Sustain. Energy Rev. 81, 1705–1720. https://doi.org/10.1016/j.rser.2017.05.261.

Bamisaye, A., Rapheal, I.A., 2021. Effect of binder type on the NaOH-treated briquettes produced from banana leaves. Biomass Convers Biorefin 13, 8939–8947. https://doi.org/10.1007/s13399-021-01771-9.

Bamisaye, A., Rapheal, I.A., 2023. Effect of binder type on the NaOH-treated briquettes produced from banana leaves. Biomass Convers Biorefin 13, 8939–8947. https://doi.org/10.1007/s13399-021-01771-9.

Bamisaye, A., Ige, A.R., Adegoke, I.A., Ogunbiyi, E.O., Bamidele, M.O., Adeleke, O., Adegoke, K.A., 2023. Eco-friendly de-lignified and raw Celosia argentea waste solid biofuel: comparative studies and machine learning modelling. Fuel 340. https://doi.org/10.1016/j.fuel.2023.127412.

Bamisaye, A., Ige, A.R., Adegoke, K.A., Adegoke, I.A., Bamidele, M.O., Alli, Y.A., Adeleke, O., Idowu, M.A., 2024. Amaranthus hybridus waste solid biofuel: comparative and machine learning studies. RSC Adv. 14, 11541–11556. https://doi.org/10.1039/d3ra08378k.

Bandara, H.M.S.C.H., Thushanth, G., Somarathna, H.M.C.C., Jayasinghe, D.H.G.A.E., Raman, S.N., 2023. Feasible techniques for valorisation of construction and demolition waste for concreting applications. Int. J. Environ. Sci. Technol. 20, 521–536. https://doi.org/10.1007/S13762-022-04015-Z/METRICS.

Barahimi, V., Ho, M., Croiset, E., 2023. From lab to fab: development and deployment of direct air capture of CO2. Energies 16, 6385. https://doi.org/10.3390/en16176385.

Barros, R.M., Tiago Filho, G.L., Santos, A.H.M., Ferreira, C.H., Pieroni, M.F., Moura, J.S., Abe, H.S. de S., Brito, L.M., dos Santos, I.F.S., Ribeiro, E.M., de Freitas, J.V.R., 2018. A potential of the biogas generating and energy recovering from municipal solid waste. Renewable Energy Focus 25, 4–16. https://doi.org/10.1016/j.ref.2018.02.001.

Baskaran, D., Saravanan, P., Nagarajan, L., Byun, H.-S., 2024. An overview of technologies for capturing, storing, and utilizing carbon dioxide: technology readiness, large-scale demonstration, and cost. Chem. Eng. J. 491, 151998. https://doi.org/10.1016/j.cej.2024.151998.

Bazooyar, B., Jomekian, A., 2024. Oxyfuel combustion as a carbon capture technique. In: Advances and Technology Development in Greenhouse Gases: Emission, Capture and Conversion. Elsevier, pp. 437–495. https://doi.org/10.1016/B978-0-443-19233-3.00023-7.

Becker, E.W., 2013. Microalgae for human and animal nutrition. Handbook of Microalgal Culture: Applied Phycology and Biotechnology, second ed., pp. 461–503. https://doi.org/10.1002/9781118567166.CH25

Bejigo, K.S., Natarajan, S., Bhunia, K., Elumalai, V., Kim, S.J., 2023. Recycling of value-added products from spent lithium-ion batteries for oxygen reduction and methanol oxidation reactions. J. Clean. Prod. 384, 135520. https://doi.org/10.1016/J.JCLEPRO.2022.135520.

Bellini, S., Tommasi, T., Fino, D., 2022. Poly(3-hydroxybutyrate) biosynthesis by Cupriavidus necator: a review on waste substrates utilization for a circular economy

approach. Bioresour. Technol. Rep. 17, 100985. https://doi.org/10.1016/j.biteb.2022.100985.
Beuttler, C., Charles, L., Wurzbacher, J., 2019. The role of direct air capture in mitigation of anthropogenic greenhouse gas emissions. Frontiers in Climate 1. https://doi.org/10.3389/fclim.2019.00010.
Bhattacharjee, S., Panja, A., Majumder, D., Hindorya, P.S., Kumar, R., 2023. From garbage to global warming: a bibliometric analysis of greenhouse gas emissions from municipal solid waste and its relationship with climate change. Environ. Dev. Sustain. 26, 10973–10998. https://doi.org/10.1007/s10668-023-04145-5.
Bisotti, F., Hoff, K.A., Mathisen, A., Hovland, J., 2024. Direct Air capture (DAC) deployment: a review of the industrial deployment. Chem. Eng. Sci. 283, 119416. https://doi.org/10.1016/j.ces.2023.119416.
Boer, D.G., Langerak, J., Pescarmona, P.P., 2023. Zeolites as selective adsorbents for CO_2 separation. ACS Appl. Energy Mater. 6, 2634–2656. https://doi.org/10.1021/acsaem.2c03605.
Boerst, J., Pena Cabra, I., Sharma, S., Zaremsky, C., Iyengar, A.K.S., 2024. Strategic siting of direct air capture facilities in the United States. Energies 17, 3755. https://doi.org/10.3390/en17153755.
Bollini, P., Diwan, M., Gautam, P., Hartman, R.L., Hickman, D.A., Johnson, M., Kawase, M., Neurock, M., Patience, G.S., Stottlemyer, A., Vlachos, D.G., Wilhite, B., 2023. Vision 2050: reaction engineering roadmap. ACS Engineering Au 3, 364–390. https://doi.org/10.1021/acsengineeringau.3c00023.
Bolotova, A., 2023. Environmental benefits of additive technologies. E3S Web of Conferences 403, 07019. https://doi.org/10.1051/E3SCONF/202340307019.
Brethauer, S., Studer, M.H.-P., 2021. Towards net zero greenhouse gas emissions in the energy and chemical sectors in Switzerland and beyond - a review. Chimia 75, 788. https://doi.org/10.2533/chimia.2021.788.
Brückner, S., Feng, Q., Ju, W., Galliani, D., Testolin, A., Klingenhof, M., Ott, S., Strasser, P., 2024. Design and diagnosis of high-performance CO2-to-CO electrolyzer cells. Nature Chemical Engineering 1, 229–239. https://doi.org/10.1038/s44286-024-00035-3.
Buddenberg, T., Bergins, C., Schmidt, S., 2016. Power to fuel as a sustainable business model for cross-sectorial energy storage in industry and power plants. CO2 as Chemical Feedstock - a Challenge for Sustainable Chemistry 6–7.
Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., Fuss, S., Galindo, A., Hackett, L.A., Hallett, J.P., Herzog, H.J., Jackson, G., Kemper, J., Krevor, S., Maitland, G.C., Matuszewski, M., Metcalfe, I.S., Petit, C., Puxty, G., Reimer, J., Reiner, D.M., Rubin, E.S., Scott, S.A., Shah, N., Smit, B., Trusler, J.P.M., Webley, P., Wilcox, J., Mac Dowell, N., 2018. Carbon capture and storage (CCS): the way forward. Energy Environ. Sci. 11, 1062–1176. https://doi.org/10.1039/c7ee02342a.
Buthelezi, A.S., Tucker, C.L., Heeres, H.J., Shozi, M.L., van de Bovenkamp, H.H., Ntola, P., 2024. Fischer-tropsch synthesis using promoted, unsupported, supported, bimetallic and spray-dried iron catalysts: a review. Results Chem 9, 101623. https://doi.org/10.1016/J.RECHEM.2024.101623.
Cabrera, G., Dickson, A., Nimubona, A.D., Quigley, J., 2022. Carbon capture, utilisation and storage: incentives, effects and policy. Int. J. Greenh. Gas Control 120. https://doi.org/10.1016/j.ijggc.2022.103756.
Carbon Utilization Research Council (CURC), Carbon Utilization Research Council (CURC), 2024. Advancing Fossil Energy Solutions.
Cardone, L.M., Petrone, G., De Rosa, S., Franco, F., Greco, C.S., 2023. Review of the recent developments about the hybrid propelled aircraft. Aerotecnica Missili & Spazio. https://doi.org/10.1007/s42496-023-00173-6.
Carmona-Martínez, A.A., Jarauta-Córdoba, C.A., 2024a. Bioconversion of industrial CO2 into synthetic fuels. https://doi.org/10.1007/978-3-031-57735-2_13.
Carmona-Martínez, A.A., Rueda, A., Jarauta-Córdoba, C.A., 2024b. Deep decarbonization of the energy intensive manufacturing industry through the bioconversion of its carbon emissions to fuels. Fuel 371, 131922. https://doi.org/10.1016/j.fuel.2024.131922.
Chataut, G., Bhatta, B., Joshi, D., Subedi, K., Kafle, K., 2023. Greenhouse gases emission from agricultural soil: a review. J Agric Food Res 11, 100533. https://doi.org/10.1016/j.jafr.2023.100533.
Chauhan, R., Sartape, R., Minocha, N., Goyal, I., Singh, M.R., 2023. Advancements in environmentally sustainable technologies for ethylene production. Energy & Fuels 37, 12589–12622. https://doi.org/10.1021/acs.energyfuels.3c01777.
Chauvy, R., De Weireld, G., 2020. CO2 utilization technologies in Europe: a short review. Energy Technol. 8. https://doi.org/10.1002/ente.202000627.
Chauvy, R., Weireld, G.D.E., 2020. CO 2 Utilization technologies in Europe: a short review. Energy Technol. 8, 2000627. https://doi.org/10.1002/ente.202000627.
Chauvy, R., Meunier, N., Thomas, D., De Weireld, G., 2019. Selecting emerging CO2 utilization products for short- to mid-term deployment. Appl. Energy 236, 662–680. https://doi.org/10.1016/j.apenergy.2018.11.096.
Chen, X., Li, J.Y., Tang, Z.R., Xu, Y.J., 2020. Surface-defect-engineered photocatalyst for nitrogen fixation into value-added chemical feedstocks. Catal. Sci. Technol. 10, 6098–6110. https://doi.org/10.1039/D0CY01227K.
Chen, Z., Wang, T., Li, C., Fang, M., Chen, W., Hu, X., Zhang, W., Zhang, li, Fan, W., Zeng, S., 2024. Research on CO2 capture performance of DMEDA water-lean absorbents based on molecular dynamics. Sep. Purif. Technol., 128924 https://doi.org/10.1016/j.seppur.2024.128924.
Cheng, F., Zhang, Y., Zhang, G., Zhang, K., Wu, J., Zhang, D., 2024. Eliminating environmental impact of coal mining wastes and coal processing by-products by high temperature oxy-fuel CFB combustion for clean power Generation: a review. Fuel 373, 132341. https://doi.org/10.1016/j.fuel.2024.132341.
Chilakamarry, C.R., Sakinah, A.M.M., Zularisam, A.W., Pandey, A., 2021. Glycerol waste to value added products and its potential applications. Systems Microbiology and Biomanufacturing 1, 378–396. https://doi.org/10.1007/s43393-021-00036-w.
Chkirida, S., Zari, N., el kacem Qaiss, A., Bouhfid, R., 2022. Future challenges and perspectives in water purification by hybrid materials. In: Nanohybrid Materials for Water Purification, pp. 217–341.
Choi, H.-J., Rhee, S.-W., 2024. The effect of waste degradation on landfill gas production in field-scale of bioreactor landfill. J. Mater. Cycles Waste Manag. 26, 400–409. https://doi.org/10.1007/s10163-023-01841-2.
Choi, Y., Sim, G.D., Jung, U., Park, Y., Youn, M.H., Chun, D.H., Rhim, G.B., Kim, K.Y., Koo, K.Y., 2024. Copper catalysts for CO2 hydrogenation to CO through reverse water–gas shift reaction for e-fuel production: fundamentals, recent advances, and prospects. Chem. Eng. J. 492, 152283. https://doi.org/10.1016/j.cej.2024.152283.
Chowdhury, S., Kumar, Y., Shrivastava, S., Patel, S.K., Sangwai, J.S., 2023. A review on the recent scientific and commercial progress on the direct air capture technology to manage atmospheric CO_2 concentrations and future perspectives. Energy & Fuels 37, 10733–10757. https://doi.org/10.1021/acs.energyfuels.2c03971.
Clomburg, J.M., Crumbley, A.M., Gonzalez, R., 2017. Industrial biomanufacturing: the future of chemical production. Science 355. https://doi.org/10.1126/science.aag0804, 1979.
Conejo, A.N., Birat, J.-P., Dutta, A., 2020. A review of the current environmental challenges of the steel industry and its value chain. J Environ Manage 259, 109782. https://doi.org/10.1016/j.jenvman.2019.109782.
Das, D., Ahmad, S., Kirshner, J., 2024. Opportunities and challenges associated with the uptake of residential clean fuel usage. Curr Environ Health Rep 11, 204–209. https://doi.org/10.1007/s40572-024-00438-7.
Davoodi, S., Al-Shargabi, M., Wood, D.A., Rukavishnikov, V.S., Minaev, K.M., 2023. Review of technological progress in carbon dioxide capture, storage, and utilization. Gas Science and Engineering 117, 205070. https://doi.org/10.1016/J.JGSCE.2023.205070.
Davoodi, S., Al-Shargabi, M., Wood, D.A., Mehrad, M., Rukavishnikov, V.S., 2024. Carbon dioxide sequestration through enhanced oil recovery: a review of storage mechanisms and technological applications. Fuel 366, 131313. https://doi.org/10.1016/j.fuel.2024.131313.
De Gelder, A., Dieleman, J.A., Bot, G.P.A., Marcelis, L.F.M., 2012. An overview of climate and crop yield in closed greenhouses. J. Hortic. Sci. Biotechnol. 87, 193–202. https://doi.org/10.1080/14620316.2012.11512852.
Deka, D.J., Jang, G.G., Kasturi, A., Stamberga, D., Keum, J.K., Custelcean, R., Tsouris, C., 2025. Pronounced reduction in the regeneration energy of potassium sarcosinate CO2 capture solvent using TiO2. Sep. Purif. Technol. 354, 128850. https://doi.org/10.1016/j.seppur.2024.128850.
Detz, R.J., Ferchaud, C.J., Kalkman, A.J., Kemper, J., Sánchez-Martínez, C., Saric, M., Shinde, M.V., 2023. Electrochemical CO_2 conversion technologies: state-of-the-art and future perspectives. Sustain. Energy Fuels 7, 5445–5472. https://doi.org/10.1039/D3SE00775H.
Deutch, J., 2016. U.S. Department of Energy, Secretary of Energy Advisory Board (SEAB) Task Force Report, CO2 Utilization and Negative Emissions Technologies. (Accessed 7 May 2020).
Dismukes, D.E., Layne, M., Snyder, B.F., 2019. Understanding the challenges of industrial carbon capture and storage: an example in a U.S. petrochemical corridor. Int. J. Sustain. Energy 38, 13–23. https://doi.org/10.1080/14786451.2018.1494172.
Dos Reis, G.S., Quattrone, M., Ambrós, W.M., Cazacliu, B.G., Sampaio, C.H., 2021. Current applications of recycled aggregates from construction and demolition: a review. Materials 2021 14, 1700. https://doi.org/10.3390/MA14071700, 1700 14.
Dutta, R., Kundu, G., Mousavi Mirkalaei, S.M., Chakraborty, R., Yomdo, S., Mandal, A., 2024. Evaluation of potential of CO_2 -enhanced oil recovery (EOR) and assessment of capacity for geological storage in a mature oil reservoir within upper Assam basin, India. Energy & Fuels. https://doi.org/10.1021/acs.energyfuels.4c02384.
Dwivedi, K.A., Huang, S.-J., Wang, C.-T., 2022. Integration of various technology-based approaches for enhancing the performance of microbial fuel cell technology: a review. Chemosphere 287, 132248. https://doi.org/10.1016/j.chemosphere.2021.132248.
Dziejarski, B., Serafin, J., Andersson, K., Krzyżyńska, R., 2023a. CO2 capture materials: a review of current trends and future challenges. Materials Today Sustainability 24, 100483. https://doi.org/10.1016/j.mtsust.2023.100483.
Dziejarski, B., Serafin, J., Andersson, K., Krzyżyńska, R., 2023b. CO2 capture materials: a review of current trends and future challenges. Materials Today Sustainability 24. https://doi.org/10.1016/j.mtsust.2023.100483.
El-Shall, N.A., Jiang, S., Farag, M.R., Azzam, M., Al-Abdullatif, A.A., Alhotan, R., Dhama, K., Hassan, F.U., Alagawany, M., 2023. Potential of Spirulina platensis as a feed supplement for poultry to enhance growth performance and immune modulation. Front. Immunol. 14, 1072787. https://doi.org/10.3389/FIMMU.2023.1072787/BIBTEX.
Elaouzy, Y., El Fadar, A., 2022. Energy, economic and environmental benefits of integrating passive design strategies into buildings: a review. Renew. Sustain. Energy Rev. 167, 112828. https://doi.org/10.1016/J.RSER.2022.112828.
Escribano, M., Horrillo, A., Mesías, F.J., 2022. Greenhouse gas emissions and carbon sequestration in organic dehesa livestock farms. Does technical-economic management matters? J. Clean. Prod. 372, 133779. https://doi.org/10.1016/j.jclepro.2022.133779.
Eze Ekechukwu, Darlington, Daramola, Gideon Oluseyi, Olanrewaju, Omowonuola Ireoluwapo Kehinde, 2024. Advancements in catalysts for zero-carbon synthetic fuel production: a comprehensive review. GSC Advanced Research and Reviews 19, 215–226. https://doi.org/10.30574/gscarr.2024.19.3.0212.
Fan, L., Zhao, Y., Chen, L., Chen, J., Chen, J., Yang, H., Xiao, Y., Zhang, T., Chen, J., Wang, L., 2023. Selective production of ethylene glycol at high rate via cascade catalysis. Nat. Catal. 6, 585–595. https://doi.org/10.1038/s41929-023-00977-6.
Fang, W., Guo, W., Lu, R., Yan, Y., Liu, X., Wu, D., Li, F.M., Zhou, Y., He, C., Xia, C., Niu, H., Wang, S., Liu, Y., Mao, Y., Zhang, C., You, B., Pang, Y., Duan, L., Yang, X.,

Song, F., Zhai, T., Wang, G., Guo, X., Tan, B., Yao, T., Wang, Z., Xia, B.Y., 2024. Durable CO2 conversion in the proton-exchange membrane system. Nature 626, 86–91. https://doi.org/10.1038/s41586-023-06917-5.

Fasihi, M., Efimova, O., Breyer, C., 2019. Techno-economic assessment of CO 2 direct air capture plants. J. Clean. Prod. 224, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086.

Ferdoush, M.R., Al Aziz, R., Karmaker, C.L., Debnath, B., Limon, M.H., Bari, A.B.M.M., 2024. Unraveling the challenges of waste-to-energy transition in emerging economies: implications for sustainability. Innovation and Green Development 3, 100121. https://doi.org/10.1016/J.IGD.2023.100121.

First, E.L., Hasan, M.M.F., 2014. Floudas christodoulos A, discovery of novel zeolites for natural gas purification through combined material screening and process optimization. AIChE J. 60, 215–228. https://doi.org/10.1002/aic.

Flessa, H., Ruser, R., Dörsch, P., Kamp, T., Jimenez, M.A., Munch, J.C., Beese, F., 2002. Integrated evaluation of greenhouse gas emissions (CO2, CH4, N2O) from two farming systems in southern Germany. Agric. Ecosyst. Environ. 91, 175–189. https://doi.org/10.1016/S0167-8809(01)00234-1.

Franco, F., Rettenmaier, C., Jeon, H.S., Roldan Cuenya, B., 2020. Transition metal-based catalysts for the electrochemical CO_2 reduction: from atoms and molecules to nanostructured materials. Chem. Soc. Rev. 49, 6884–6946. https://doi.org/10.1039/D0CS00835D.

Frank-collins, J., Greenberg, S., Gupta, N., Haagsma, A., 2022. A case study strategic CCUS communications across a 20-state region of the United States. https://dx.doi.org/10.2139/ssrn.4286386.

Fu, L., Ren, Z., Si, W., Ma, Q., Huang, W., Liao, K., Huang, Z., Wang, Y., Li, J., Xu, P., 2022. Research progress on CO2 capture and utilization technology. J. CO2 Util. 66. https://doi.org/10.1016/j.jcou.2022.102260.

Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., De Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.V., Wilcox, J., Del Mar Zamora Dominguez, M., Minx, J.C., 2018. Negative emissions - Part 2: costs, potentials and side effects. Environ. Res. Lett. 13, 063002. https://doi.org/10.1088/1748-9326/aabf9f.

Gabrielli, P., Gazzani, M., Mazzotti, M., 2020. The role of carbon capture and utilization, carbon capture and storage, and biomass to enable a net-zero-CO_2 emissions chemical industry. Ind. Eng. Chem. Res. 59, 7033–7045. https://doi.org/10.1021/acs.iecr.9b06579.

García-Bordejé, E., González-Olmos, R., 2024a. Advances in process intensification of direct air CO2 capture with chemical conversion. Prog. Energy Combust. Sci. 100, 101132. https://doi.org/10.1016/j.pecs.2023.101132.

García-Bordejé, E., González-Olmos, R., 2024b. Advances in process intensification of direct air CO2 capture with chemical conversion. Prog. Energy Combust. Sci. 100, 101132. https://doi.org/10.1016/j.pecs.2023.101132.

Garg, S., Li, M., Weber, A.Z., Ge, L., Li, L., Rudolph, V., Wang, G., Rufford, T.E., 2020. Advances and challenges in electrochemical CO_2 reduction processes: an engineering and design perspective looking beyond new catalyst materials. J Mater Chem A Mater 8, 1511–1544. https://doi.org/10.1039/C9TA13298H.

Garnett, T., 2009. Livestock-related greenhouse gas emissions: impacts and options for policy makers. Environ Sci Policy 12, 491–503. https://doi.org/10.1016/j.envsci.2009.01.006.

Gautam, A., Mondal, M.K., 2023. Review of recent trends and various techniques for CO2 capture: special emphasis on biphasic amine solvents. Fuel 334, 126616. https://doi.org/10.1016/j.fuel.2022.126616.

Ghosh, A., Misra, S., Bhattacharyya, R., Sarkar, A., Singh, A.K., Tyagi, V.C., Kumar, R.V., Meena, V.S., 2020. Agriculture, dairy and fishery farming practices and greenhouse gas emission footprint: a strategic appraisal for mitigation. Environ. Sci. Pollut. Control Ser. 27, 10160–10184. https://doi.org/10.1007/s11356-020-07949-4.

Gogna, S., Kaur, J., Sharma, K., Prasad, R., Singh, J., Bhadariya, V., Kumar, P., Jarial, S., 2023. Spirulina- an edible cyanobacterium with potential therapeutic health benefits and toxicological consequences. Journal of the American Nutrition Association 42, 559–572. https://doi.org/10.1080/27697061.2022.2103852.

Goli, A., Shamiri, A., Talaiekhozani, A., Eshtiaghi, N., Aghamohammadi, N., Aroua, M.K., 2016. An overview of biological processes and their potential for CO2 capture. J Environ Manage 183, 41–58. https://doi.org/10.1016/j.jenvman.2016.08.054.

Goren, A.Y., Dincer, I., Gogoi, S.B., Boral, P., Patel, D., 2024. Recent developments on carbon neutrality through carbon dioxide capture and utilization with clean hydrogen for production of alternative fuels for smart cities. Int. J. Hydrogen Energy 79, 551–578. https://doi.org/10.1016/j.ijhydene.2024.06.421.

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., Murphy, J.D., 2021. Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Advances in Applied Energy 1, 100008. https://doi.org/10.1016/j.adapen.2021.100008.

Grim, R.G., Huang, Z., Guarnieri, M.T., Ferrell, J.R., Tao, L., Schaidle, J.A., 2020. Transforming the carbon economy: challenges and opportunities in the convergence of low-cost electricity and reductive CO_2 utilization. Energy Environ. Sci. 13, 472–494. https://doi.org/10.1039/C9EE02410G.

Guo, Y., Luo, L., Liu, T., Hao, L., Li, Y., Liu, P., Zhu, T., 2024. A review of low-carbon technologies and projects for the global cement industry. Journal of Environmental Sciences 136, 682–697. https://doi.org/10.1016/j.jes.2023.01.021.

Gupta, R., Mishra, A., Thirupathaiah, Y., Chandel, A.K., 2024. Biochemical conversion of CO2 in fuels and chemicals: status, innovation, and industrial aspects. Biomass Convers Biorefin 14, 3007–3030. https://doi.org/10.1007/s13399-022-02552-8.

Gür, T.M., 2022. Carbon dioxide emissions, capture, storage and utilization: review of materials, processes and technologies. Prog. Energy Combust. Sci. 89, 100965. https://doi.org/10.1016/j.pecs.2021.100965.

Gutsch, M., Leker, J., 2024. Co-assessment of costs and environmental impacts for off-grid direct air carbon capture and storage systems. Communications Engineering 3, 14. https://doi.org/10.1038/s44172-023-00152-6.

Han, S.H., Kim, S.M., Jun, Y., Han, T.H., Kim, J.H., 2024. Carbon-captured sodium hydroxide solution for sustainable alkali-activated slag. Sustainable Materials and Technologies 40, e00915. https://doi.org/10.1016/j.susmat.2024.e00915.

Hills, C.D., Tripathi, N., Singh, R.S., Carey, P.J., Lowry, F., 2020. Valorisation of agricultural biomass-ash with CO2. Sci. Rep. 10, 13801. https://doi.org/10.1038/s41598-020-70504-1.

Ho, H.-J., Iizuka, A., 2024. Applications of CO2 mineralization for carbon capture, utilization, and storage. In: Advances and Technology Development in Greenhouse Gases: Emission, Capture and Conversion. Elsevier, pp. 403–430. https://doi.org/10.1016/B978-0-443-19231-9.00025-9.

Horbach, J., Rammer, C., Rennings, K., 2012. Determinants of eco-innovations by type of environmental impact - the role of regulatory push/pull, technology push and market pull. Ecol. Econ. 78, 112–122. https://doi.org/10.1016/j.ecolecon.2012.04.005.

Hosseini, S.E., Wahid, M.A., 2016. Hydrogen production from renewable and sustainable energy resources: promising green energy carrier for clean development. Renew. Sustain. Energy Rev. 57, 850–866. https://doi.org/10.1016/J.RSER.2015.12.112.

Hu, X., Assaad, R.H., 2024. A BIM-enabled digital twin framework for real-time indoor environment monitoring and visualization by integrating autonomous robotics, LiDAR-based 3D mobile mapping, IoT sensing, and indoor positioning technologies. J. Build. Eng. 86, 108901. https://doi.org/10.1016/j.jobe.2024.108901.

Hu, Y., Gani, R., Sundmacher, K., Zhou, T., 2024. Assessing the future impact of 12 direct air capture technologies. Chem. Eng. Sci. 298, 120423. https://doi.org/10.1016/j.ces.2024.120423.

Huang, G.H., Chen, F., Wei, D., Zhang, X.W., Chen, G., 2018. Biodiesel production by microalgal biotechnology. Renew. Energy 378–395. https://doi.org/10.4324/9781315793245-106/BIODIESEL-PRODUCTION-MICROALGAL-BIOTECHNOLOGY-GUANHUA-HUANG-FENG-CHEN-DONG-WEI-XUEWU-ZHANG-GU-CHEN. Four Volume Set 3–4.

Huang, W., Hendra Pratama, R., Oguma, M., Kinoshita, K., Takeda, Y., Suzuki, S., 2023. Spray dynamics of synthetic dimethyl carbonate and its blends with gasoline. Fuel 341, 127696. https://doi.org/10.1016/J.FUEL.2023.127696.

Huang, T., Ma, J., Song, S., Ling, Z., Macdonald, R.W., Gao, H., Tao, S., Shen, H., Liu, J., Tian, C., Zhao, Y., Liu, X., Chen, K., Mao, X., 2024. Food shortage driven crop residue burning and health risk. J. Clean. Prod. 448, 141645. https://doi.org/10.1016/j.jclepro.2024.141645.

Huijts, N.M.A., Molin, E.J.E., Steg, L., 2012. Psychological factors influencing sustainable energy technology acceptance: a review-based comprehensive framework. Renew. Sustain. Energy Rev. 16, 525–531. https://doi.org/10.1016/j.rser.2011.08.018.

Humpenöder, F., Bodirsky, B.L., Weindl, I., Lotze-Campen, H., Linder, T., Popp, A., 2022. Projected environmental benefits of replacing beef with microbial protein. Nature 605 (7908 605), 90–96. https://doi.org/10.1038/s41586-022-04629-w, 2022.

Idowu, I.A., Atherton, W., Hashim, K., Kot, P., Alkhaddar, R., Alo, B.I., Shaw, A., 2019. An analyses of the status of landfill classification systems in developing countries: sub Saharan Africa landfill experiences. Waste Management 87, 761–771. https://doi.org/10.1016/j.wasman.2019.03.011.

IEA, 2020. Energy Technology Perspectives 2020. IEA, Paris.

IPCC, 2021. Climate change 2021: the physical science basis | climate change 2021. The Physical Science Basis. https://www.ipcc.ch/report/ar6/wg1/. (Accessed 9 August 2024).

Irfan, M., Musarat, M.A., Alaloul, W.S., Ghufran, M., 2024. Chapter Eight - radiative forcing on climate change: assessing the effect of greenhouse gases on energy balance of Earth. In: Rahimpour, M.R., Makarem, M.A., A, M.B.T., T.D (Eds.), G.G.E. Meshksar Capture and Conversion. Elsevier, pp. 137–167. https://doi.org/10.1016/B978-0-443-19066-7.00012-6.

Islam Rony, Z., Mofijur, M., Hasan, M.M., Rasul, M.G., Jahirul, M.I., Forruque Ahmed, S., Kalam, M.A., Anjum Badruddin, I., Yunus Khan, T.M., Show, P.-L., 2023. Alternative fuels to reduce greenhouse gas emissions from marine transport and promote UN sustainable development goals. Fuel 338, 127220. https://doi.org/10.1016/j.fuel.2022.127220.

Izumi, Y., Iizuka, A., Ho, H.-J., 2021. Calculation of greenhouse gas emissions for a carbon recycling system using mineral carbon capture and utilization technology in the cement industry. J. Clean. Prod. 312, 127618. https://doi.org/10.1016/j.jclepro.2021.127618.

Jerng, S.E., Park, Y.J., Li, J., 2024. Machine learning for CO2 capture and conversion: a review. Energy and AI 16. https://doi.org/10.1016/j.egyai.2024.100361.

Ji, W., Liu, J., Sha, C., Yong, Y.-C., Jiang, Y., Fang, Z., 2024. Nanomaterial-biological hybrid systems: advancements in solar-driven CO2-to-Chemical conversion. Green Carbon. https://doi.org/10.1016/j.greenca.2024.05.005.

Jin, C., Li, X., Xu, T., Dong, J., Geng, Z., Liu, J., Ding, C., Hu, J., El Alaoui, A., Zhao, Q., Liu, H., 2023. Zero-carbon and carbon-neutral fuels: a review of combustion products and cytotoxicity. Energies 2023 16, 6507. https://doi.org/10.3390/EN16186507, 6507 16.

Kamran, M., Turzyński, M., 2024. Exploring hydrogen energy systems: a comprehensive review of technologies, applications, prevailing trends, and associated challenges. J. Energy Storage 96, 112601. https://doi.org/10.1016/j.est.2024.112601.

Kanjilal, B., Nabavinia, M., Masoumi, A., Savelski, M., Noshadi, I., 2020. Challenges on CO2 Capture, Utilization, and Conversion. Elsevier Inc. https://doi.org/10.1016/B978-0-12-819657-1.00002-5

Kappis, K., Papavasiliou, J., Avgouropoulos, G., 2021. Methanol reforming processes for fuel cell applications. Energies 2021 14, 8442. https://doi.org/10.3390/EN14248442. Page 8442 14.

Karishma, S., Kamalesh, R., Saravanan, A., Deivayanai, V.C., Yaashikaa, P.R., Vickram, A.S., 2024. A review on recent advancements in biochemical fixation and transformation of CO2 into constructive products. Biochem. Eng. J. 208, 109366. https://doi.org/10.1016/j.bej.2024.109366.

Kassam, A., Kassam, L., 2021. Paradigms of agriculture. In: Rethinking Food and Agriculture. Elsevier, pp. 181–218. https://doi.org/10.1016/B978-0-12-816410-5.00010-4.

Keijzer, C.J., Smulders, L.C.J., Wezendonk, D., de Rijk, J.W., de Jongh, P.E., 2024. Influence of Ag particle size and Ag : Al2O3 surface ratio in catalysts for the chloride-promoted ethylene epoxidation. Catal. Today 428, 114447. https://doi.org/10.1016/j.cattod.2023.114447.

Kibria, M.G., Edwards, J.P., Gabardo, C.M., Dinh, C.T., Seifitokaldani, A., Sinton, D., Sargent, E.H., 2019. Electrochemical CO2 reduction into chemical feedstocks: from mechanistic electrocatalysis models to system design. Adv. Mater. 31, 1807166. https://doi.org/10.1002/ADMA.201807166.

Kiehbadroudinezhad, M., Merabet, A., Hosseinzadeh-Bandbafha, H., 2024. Chapter Six - landfill source of greenhouse gas emission. In: M.R. Rahimpour, M.A. Makarem, M.B. T.-A, T.D, Meshksar, G.G.E. (Eds.), Capture and Conversion. Elsevier, pp. 123–145. https://doi.org/10.1016/B978-0-443-19231-9.00023-5.

Köpke, M., Simpson, S.D., 2020. Pollution to products: recycling of 'above ground' carbon by gas fermentation. Curr. Opin. Biotechnol. 65, 180–189. https://doi.org/10.1016/j.copbio.2020.02.017.

Koytsoumpa, E.I., Bergins, C., Buddenberg, T., Wu, S., Sigurbjörnsson, Ó., Tran, K.C., Kakaras, E., 2016. The challenge of energy storage in Europe: focus on power to fuel. Journal of Energy Resources Technology, Transactions of the ASME 138, 1–10. https://doi.org/10.1115/1.4032544.

Koytsoumpa, E.I., Bergins, C., Kakaras, E., 2018. The CO2 economy: review of CO2 capture and reuse technologies. J. Supercrit. Fluids 132, 3–16. https://doi.org/10.1016/j.supflu.2017.07.029.

Kraus, C., Jakubec, P., Girhe, S., Fellner, F., Jaensch, M., Wachtmeister, G., Pitsch, H., 2022. Adaptation and engine validation of an FTIR exhaust gas analysis method for C1-based potential GHG-neutral synthetic fuels/gasoline-blends containing dimethyl carbonate and methyl formate. SAE Technical Papers. https://doi.org/10.4271/2022-01-0569.

Kryeziu, D., Selmani, F., Mujaj, A., Kondi, I., 2023. Recycled concrete aggregates: a promising and sustainable option for the construction industry. Journal of Human, Earth, and Future 4, 166–180. https://doi.org/10.28991/HEF-2023-04-02-03.

Kumar, J.A., Sathish, S., Prabu, D., Renita, A.A., Saravanan, A., Deivayanai, V.C., Anish, M., Jayaprabakar, J., Baigenzhenov, O., Hosseini-Bandegharaei, A., 2023a. Agricultural waste biomass for sustainable bioenergy production: feedstock, characterization and pre-treatment methodologies. Chemosphere 331, 138680. https://doi.org/10.1016/J.CHEMOSPHERE.2023.138680.

Kumar, N., Chaudhary, A., Ahlawat, O.P., Naorem, A., Upadhyay, G., Chhokar, R.S., Gill, S.C., Khippal, A., Tripathi, S.C., Singh, G.P., 2023b. Crop residue management challenges, opportunities and way forward for sustainable food-energy security in India: a review. Soil Tillage Res. 228, 105641. https://doi.org/10.1016/j.still.2023.105641.

Lam, M.K., Lee, K.T., Mohamed, A.R., 2012. Current status and challenges on microalgae-based carbon capture. Int. J. Greenh. Gas Control 10, 456–469. https://doi.org/10.1016/j.ijggc.2012.07.010.

Lamichhane, P., Pourali, N., Scott, L., Tran, N.N., Lin, L., Gelonch, M.E., V Rebrov, E., Hessel, V., 2024. Critical review: 'Green' ethylene production through emerging technologies, with a focus on plasma catalysis. Renew. Sustain. Energy Rev. 189, 114044. https://doi.org/10.1016/j.rser.2023.114044.

Li, G., Yao, J., 2024. Direct air capture (DAC) for achieving net-zero CO2 emissions: advances, applications, and challenges. Eng 5, 1298–1336. https://doi.org/10.3390/eng5030069.

Li, L., Zhao, N., Wei, W., Sun, Y., 2013. A review of research progress on CO2 capture, storage, and utilization in Chinese Academy of Sciences. Fuel 108, 112–130. https://doi.org/10.1016/j.fuel.2011.08.022.

Li, J., Li, Y., Wan, Y., Wang, B., Cai, W., Qin, X., Zhou, Z., Wang, X., Yuan, J., Deng, Q., 2024a. Annual greenhouse gas emissions from a rice paddy with different water-nitrogen management strategies in Central China. Soil Tillage Res. 235, 105906. https://doi.org/10.1016/j.still.2023.105906.

Li, Y., Tian, H., Yao, Y., Shi, H., Bian, Z., Shi, Y., Wang, S., Maavara, T., Lauerwald, R., Pan, S., 2024b. Increased nitrous oxide emissions from global lakes and reservoirs since the pre-industrial era. Nat. Commun. 15, 942. https://doi.org/10.1038/s41467-024-45061-0.

Lin, N., Xu, L., 2024. Navigating the implementation of tax credits for natural-gas-based low-carbon-intensity hydrogen projects. Energies 17, 1604. https://doi.org/10.3390/en17071604.

Liu, W., Teng, L., Rohani, S., Qin, Z., Zhao, B., Xu, C.C., Ren, S., Liu, Q., Liang, B., 2021. CO2 mineral carbonation using industrial solid wastes: a review of recent developments. Chem. Eng. J. 416, 129093. https://doi.org/10.1016/j.cej.2021.129093.

Liu, S., Gao, Q., Wu, J., Xie, Y., Yang, Q., Wang, R., Zhang, J., Liu, Q., 2022a. Spatial distribution and influencing mechanism of CO2, N2O and CH4 in the Pearl River Estuary in summer. Sci. Total Environ. 846, 157381. https://doi.org/10.1016/j.scitotenv.2022.157381.

Liu, J., Gong, E., Wang, X., 2022b. Economic benefits of construction waste recycling enterprises under tax incentive policies. Environ. Sci. Pollut. Control Ser. 29, 12574–12588. https://doi.org/10.1007/S11356-021-13831-8/METRICS.

Liu, X., Li, L., Zhao, G., Xiong, P., 2024a. Optimization strategies for CO2 biological fixation. Biotechnol. Adv. 73, 108364. https://doi.org/10.1016/j.biotechadv.2024.108364.

Liu, H., Song, T., Wang, Y., Zhang, X., Cui, L., Liu, T., Yuan, Z., 2024b. Efficient electrocatalytic reduction of CO2 to CO via mechanochemical synthesized copper-based composite metallic oxide catalyst. J. Porous Mater. 31, 437–448. https://doi.org/10.1007/s10934-023-01524-1.

López, L.R., Dessì, P., Cabrera-Codony, A., Rocha-Melogno, L., Kraakman, N.J.R., Balaguer, M.D., Puig, S., 2024. Indoor CO2 direct air capture and utilization: key strategies towards carbon neutrality. Clean Eng Technol 20, 100746. https://doi.org/10.1016/j.clet.2024.100746.

Lou, Y., Zhang, Z., Li, T., Zhang, Y., Chen, W., 2024. Compressibility characteristics of municipal solid waste considering multiple factors. Environ. Sci. Pollut. Control Ser. 31, 44401–44414. https://doi.org/10.1007/s11356-024-34176-y.

Lu, Q., Li, H., Xiao, Y., Liu, H., 2021. A state-of-the-art review on the synthetic mechanisms, production technologies, and practical application of polyunsaturated fatty acids from microalgae. Algal Res. 55, 102281. https://doi.org/10.1016/j.algal.2021.102281.

Lu, G., Wang, Z., Yue, Z., Yang, L., Zhang, X., Huang, Y., Qian, J., Fan, X., 2024. A novel non-aqueous tertiary amine system for low energy CO2 capture developed via molecular dynamics simulation. Sep. Purif. Technol. 354, 128996. https://doi.org/10.1016/j.seppur.2024.128996.

L'Orange Seigo, S., Dohle, S., Siegrist, M., 2014. Public perception of carbon capture and storage (CCS): a review. Renew. Sustain. Energy Rev. 38, 848–863. https://doi.org/10.1016/j.rser.2014.07.017.

Mabuchi, H., Irie, T., Sakai, J., Das, S., Negishi, Y., 2024. Covalent organic frameworks: cutting-edge materials for carbon dioxide capture and water harvesting from air. Chem. Eur J. 30. https://doi.org/10.1002/chem.202303474.

Mahmood, T., Hussain, N., Shahbaz, A., Mulla, S.I., Iqbal, H.M.N., Bilal, M., 2023. Sustainable production of biofuels from the algae-derived biomass. Bioprocess Biosyst Eng 46, 1077–1097. https://doi.org/10.1007/s00449-022-02796-8.

Mahmoudi Kouhi, R., Jebrailvand Moghaddam, M.M., Doulati Ardejani, F., Mirheydari, A., Maghsoudy, S., Gholizadeh, F., Ghobadipour, B., 2024. Carbon Utilization Technologies & Methods, pp. 1–50. https://doi.org/10.1007/978-3-031-46590-1_1.

Malico, I., 2024. In: Gonçalves, A.C., Malico, I. (Eds.), Biomass for Domestic Heat BT - Forest Bioenergy: from Wood Production to Energy Use. Springer International Publishing, Cham, pp. 209–233. https://doi.org/10.1007/978-3-031-48224-3_8.

Mariappan, S., David Raj, A., Kumar, S., Chatterjee, U., 2022. In: Chatterjee, U., Akanwa, A.O., Kumar, S., Singh, S.K., Dutta Roy, A. (Eds.), Global Warming Impacts on the Environment in the Last Century BT - Ecological Footprints of Climate Change : Adaptive Approaches and Sustainability. Springer International Publishing, Cham, pp. 63–93. https://doi.org/10.1007/978-3-031-15501-7_3.

Maselli, G., Oliva, G., Nesticò, A., Belgiorno, V., Naddeo, V., Zarra, T., 2024. Carbon capture and utilisation (CCU) solutions: assessing environmental, economic, and social impacts using a new integrated methodology. Sci. Total Environ. 948, 174873. https://doi.org/10.1016/j.scitotenv.2024.174873.

Mbazima, S.J., Masekameni, M.D., Mmereki, D., 2022. Waste-to-energy in a developing country: The state of landfill gas to energy in the Republic of South Africa. Energy Exploration & Exploitation 40, 1287–1312. https://doi.org/10.1177/01445987221084376.

McLaughlin, H., Littlefield, A.A., Menefee, M., Kinzer, A., Hull, T., Sovacool, B.K., Bazilian, M.D., Kim, J., Griffiths, S., 2023a. Carbon capture utilization and storage in review: sociotechnical implications for a carbon reliant world. Renew. Sustain. Energy Rev. 177, 113215. https://doi.org/10.1016/J.RSER.2023.113215.

McLaughlin, H., Littlefield, A.A., Menefee, M., Kinzer, A., Hull, T., Sovacool, B.K., Bazilian, M.D., Kim, J., Griffiths, S., 2023b. Carbon capture utilization and storage in review: sociotechnical implications for a carbon reliant world. Renew. Sustain. Energy Rev. 177, 113215. https://doi.org/10.1016/j.rser.2023.113215.

Mechtcherine, V., Wyrzykowski, M., Schröfl, C., Snoeck, D., Lura, P., De Belie, N., Mignon, A., Van Vlierberghe, S., Klemm, A.J., Almeida, F.C.R., Tenório Filho, J.R., Boshoff, W.P., Reinhardt, H.W., Igarashi, S.I., 2021. Application of super absorbent polymers (SAP) in concrete construction—update of RILEM state-of-the-art report. Mater. Struct. 54 (2 54), 1–20. https://doi.org/10.1617/S11527-021-01668-Z, 2021.

Mei, D., Qiu, X., Liu, H., Wu, Q., Yu, S., Xu, L., Zuo, T., Wang, Y., 2022. Progress on methanol reforming technologies for highly efficient hydrogen production and applications. Int. J. Hydrogen Energy 47, 35757–35777. https://doi.org/10.1016/J.IJHYDENE.2022.08.134.

Melo Bravo, P., Debecker, D.P., 2019. Combining CO2 capture and catalytic conversion to methane. Waste Dispos Sustain Energy 1, 53–65. https://doi.org/10.1007/s42768-019-00004-0.

Mias, M., Sialas, K., Govorukha, K., Mayer, P., 2020. Costs and Benefits of Political and Physical Collaboration in the European Power Market. ECONSTOR. https://hdl.handle.net/10419/226807.

Mihalcea, C., Burton, F., Conrado, R., Simpson, S., 2023. R& D& I and industry examples: LanzaTech's gas fermentation. https://doi.org/10.1007/978-3-031-27811-2_27.

Mishra, S., Perkovich, P.M., Mitchell, W.P., Venkataraman, M., Pfleger, B.F., 2024. Expanding the synthetic biology toolbox of Cupriavidus necator for establishing fatty acid production. J. Ind. Microbiol. Biotechnol. 51. https://doi.org/10.1093/jimb/kuae008.

Mneimneh, F., Haddad, N., Ramakrishna, S., 2024. Recycle and reuse to reduce plastic waste - a perspective study comparing petro- and bioplastics. Circular Economy and Sustainability. https://doi.org/10.1007/s43615-024-00381-7.

Modupe Abati, S., Bamisaye, A., Abidemi Adaramaja, A., Rapheal Ige, A., Adegoke, K.A., Olurotimi Ogunbiyi, E., Abidemi Idowu, M., Olabintan, A.B., Saleh, T.A., 2024. Biodiesel production from spent vegetable oil with Al2O3 and Fe2O3-biobased heterogenous nanocatalysts: comparative and optimization studies. Fuel 364. https://doi.org/10.1016/j.fuel.2023.130847.

Mohammed, S., Eljack, F., Al-Sobhi, S., Kazi, M.-K., 2024. A systematic review: the role of emerging carbon capture and conversion technologies for energy transition to clean hydrogen. J. Clean. Prod. 447, 141506. https://doi.org/10.1016/j.jclepro.2024.141506.
Monteagudo, J.M., Durán, A., Alonso, M., Stoica, A.-I., 2024. Investigation of effectiveness of KOH-activated olive pomace biochar for efficient direct air capture of CO2. Sep. Purif. Technol. 352, 127997. https://doi.org/10.1016/j.seppur.2024.127997.
Moreno-Gonzalez, M., Berger, A., Borsboom-Hanson, T., Mérida, W., 2021. Carbon-neutral fuels and chemicals: economic analysis of renewable syngas pathways via CO2 electrolysis. Energy Convers. Manag. 244, 114452. https://doi.org/10.1016/J.ENCONMAN.2021.114452.
Murphy, R., 2024. What is undermining climate change mitigation? How fossil-fuelled practices challenge low-carbon transitions. Energy Res Soc Sci 108, 103390. https://doi.org/10.1016/j.erss.2023.103390.
Muthuraj, R., Mekonnen, T., 2018. Recent progress in carbon dioxide (CO2) as feedstock for sustainable materials development: Co-polymers and polymer blends. Polymer (Guildf) 145, 348–373. https://doi.org/10.1016/j.polymer.2018.04.078.
Nabila, D.S., Chan, R., Syamsuri, R.R.P., Nurlilasari, P., Wan-Mohtar, W.A.A.Q.I., Ozturk, A.B., Rossiana, N., Doni, F., 2024. Biobutanol production from underutilized substrates using Clostridium: unlocking untapped potential for sustainable energy development. Curr Res Microb Sci 7, 100250. https://doi.org/10.1016/j.crmicr.2024.100250.
NASA, 2024. Climate change - NASA science. https://science.nasa.gov/climate-change/. (Accessed 9 August 2024).
Nguyen, L.H., Nguyen, T.D., Tran, T.V.N., Nguyen, D.L., Tran, H.S., Nguyen, T.L., Nguyen, T.H., Nguyen, H.G., Nguyen, T.P., Nguyen, N.T., Isawa, T., Ta, Y., Sato, R., 2022. Steel slag quality control for road construction aggregates and its environmental impact: case study of Vietnamese steel industry—leaching of heavy metals from steel-making slag. Environ. Sci. Pollut. Control Ser. 29, 41983–41991. https://doi.org/10.1007/S11356-021-16438-1/METRICS.
Nie, W., Heim, G.P., Watkins, N.B., Agapie, T., Peters, J.C., 2023. Organic additive-derived films on Cu electrodes promote electrochemical CO2 reduction to C2+ products under strongly acidic conditions. Angew. Chem. Int. Ed. 62, e202216102. https://doi.org/10.1002/ANIE.202216102.
Nielsen, J.A.E., Stavrianakis, K., Morrison, Z., 2022. Community acceptance and social impacts of carbon capture, utilization and storage projects: a systematic meta-narrative literature review. https://doi.org/10.1371/journal.pone.0272409.
Nnabuife, S.G., Hamzat, A.K., Whidborne, J., Kuang, B., Jenkins, K.W., 2024a. Integration of renewable energy sources in tandem with electrolysis: a technology review for green hydrogen production. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2024.06.342.
Nnabuife, S.G., Hamzat, A.K., Whidborne, J., Kuang, B., Jenkins, K.W., 2024b. Integration of renewable energy sources in tandem with electrolysis: a technology review for green hydrogen production. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2024.06.342.
Nyirenda, H., 2023. Fiddling at the conference of the parties? Peeping into the highs and lows of the post-Kyoto climate change conferences: a review on contexts, decisions and implementation highlights. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-023-04277-8.
Obi, C.C., Nwabanne, J.T., Igbokwe, P.K., Idumah, C.I., Okpechi, V.U., Oyeoka, H.C., 2024. Novel advances in synthesis and catalytic applications of metal-organic frameworks - based nanocatalysts for CO2 capture and transformation. J. Environ. Chem. Eng. 12, 112835. https://doi.org/10.1016/j.jece.2024.112835.
Ogundele, O.D., Amoo, I.A., Adesina, A.O., Abidemi, A., Bisi-Omotosho, A., 2024. Biotechnology for renewable fuel and chemicals. In: Microbial Biotechnology for Bioenergy. Elsevier, pp. 325–345. https://doi.org/10.1016/B978-0-443-14112-6.00016-X.
Oke, D., Dunn, J.B., Hawkins, T.R., 2024. Reducing economy-wide greenhouse gas emissions with electrofuels and biofuels as the grid decarbonizes. Energy & Fuels 38, 6048–6061. https://doi.org/10.1021/acs.energyfuels.3c04833.
Olabi, A.G., Wilberforce, T., Elsaid, K., Sayed, E.T., Maghrabie, H.M., Abdelkareem, M.A., 2022. Large scale application of carbon capture to process industries – a review. J. Clean. Prod. 362, 132300. https://doi.org/10.1016/j.jclepro.2022.132300.
Oladoye, P.O., Omotola, E.O., Alli, Y.A., Oladipo, M.E., Ejeromedoghene, O., Bamisaye, A., 2024. The politics and policies of bioenergy advancement: a global perspective. In: Maddela, N.R., Aransiola, S.A., Ezugwu, C.I., Winkelstroter Eller, L.K., Scalvenzi, L., Meng, F. (Eds.), Microbial Biotechnology for Bioenergy. Elsevier, pp. 299–324. https://doi.org/10.1016/b978-0-443-14112-6.00015-8.
Olfe-Kräutlein, B., Strunge, T., Chanin, A., 2021. Push or pull? Policy barriers and incentives to the development and deployment of CO2 utilization, in particular CO2 mineralization. Front. Energy Res. 9, 1–12. https://doi.org/10.3389/fenrg.2021.742709.
Omodolor, I.S., Otor, H.O., Andonegui, J.A., Allen, B.J., Alba-Rubio, A.C., 2020. Dual-function materials for CO2Capture and conversion: a review. Ind. Eng. Chem. Res. 59, 17612–17631. https://doi.org/10.1021/acs.iecr.0c02218.
Osman, A.I., Chen, Z., Elgarahy, A.M., Farghali, M., Mohamed, I.M.A., Priya, A.K., Hawash, H.B., Yap, P., 2024. Membrane technology for energy saving: principles, techniques, applications, challenges, and prospects. Advanced Energy and Sustainability Research 5. https://doi.org/10.1002/aesr.202400011.
Ottenbros, A.B., van Zelm, R., Simons, J., van der Hulst, M.K., de Kleijne, K., de Neve, H., Huijbregts, M.A.J., 2024a. Prospective environmental burdens and benefits of fast-swing direct air carbon capture and storage. Sci. Rep. 14, 16549. https://doi.org/10.1038/s41598-024-66990-2.
Ottenbros, A.B., van Zelm, R., Simons, J., van der Hulst, M.K., de Kleijne, K., de Neve, H., Huijbregts, M.A.J., 2024b. Prospective environmental burdens and benefits of fast-swing direct air carbon capture and storage. Sci. Rep. 14, 16549. https://doi.org/10.1038/s41598-024-66990-2.
Ozkan, M., 2024a. Atmospheric alchemy: the energy and cost dynamics of direct air carbon capture. MRS Energy & Sustainability. https://doi.org/10.1557/s43581-024-00091-5.
Ozkan, M., 2024b. Atmospheric alchemy: the energy and cost dynamics of direct air carbon capture. MRS Energy and Sustainability 1–16. https://doi.org/10.1557/s43581-024-00091-5.
Pamu, Y., Alugubelli, S., 2023. A comparative study of environmental impacts due to conventional and sustainable concrete. Mater Today Proc 92, 112–120. https://doi.org/10.1016/j.matpr.2023.03.817.
Patil, T., Naji, A., Mondal, U., Pandey, I., Unnarkat, A., Dharaskar, S., 2024. Sustainable methanol production from carbon dioxide: advances, challenges, and future prospects. Environ. Sci. Pollut. Control Ser. 31, 44608–44648. https://doi.org/10.1007/s11356-024-34139-3.
Perpiñán, J., Peña, B., Bailera, M., Eveloy, V., Kannan, P., Raj, A., Lisbona, P., Romeo, L.M., 2023. Integration of carbon capture technologies in blast furnace based steel making: a comprehensive and systematic review. Fuel 336, 127074. https://doi.org/10.1016/j.fuel.2022.127074.
Piccoli, I., Polese, R., Berti, A., 2024. Low efficacy of different crop residue management on C and N stocks after five decades. Soil Tillage Res. 244, 106224. https://doi.org/10.1016/j.still.2024.106224.
Pontius, J., McIntosh, A., 2024. Regenerative agriculture. https://doi.org/10.1007/978-3-031-48762-0_11.
Position Paper CVE CCU in EU Policy-Landscape, CO2 Value Europe, 2022.
Postweiler, P., Engelpracht, M., Rezo, D., Gibelhaus, A., von der Assen, N., 2024. Environmental process optimisation of an adsorption-based direct air carbon capture and storage system. Energy Environ. Sci. 17, 3004–3020. https://doi.org/10.1039/D3EE02970K.
Qin, Z., Canter, C.E., Dunn, J.B., Mueller, S., Kwon, H., Han, J., Wander, M.M., Wang, M., 2018. Land management change greatly impacts biofuels' greenhouse gas emissions. GCB Bioenergy 10, 370–381. https://doi.org/10.1111/gcbb.12500.
Quang, D.V., Milani, D., Abu Zahra, M., 2023. A review of potential routes to zero and negative emission technologies via the integration of renewable energies with CO2 capture processes. Int. J. Greenh. Gas Control 124, 103862. https://doi.org/10.1016/j.ijggc.2023.103862.
Quataert, K., Verhoeven, E., De Winter, K., Waegeman, H., 2023. Piloting, scale-up, and demonstration. https://doi.org/10.1007/978-3-031-27811-2_34.
Qureshi, A.H., Alaloul, W.S., Murtiyoso, A., Hussain, S.J., Saad, S., Musarat, M.A., 2024. Smart rebar progress monitoring using 3D point cloud model. Expert Syst. Appl. 249, 123562. https://doi.org/10.1016/j.eswa.2024.123562.
Rafique, H., 2018. 5.15 energy management in network systems. Comprehensive Energy Systems: Volumes 1-5 5, 581–647. https://doi.org/10.1016/B978-0-12-809597-3.00531-9.
Raganati, F., Ammendola, P., 2024. CO_2 post-combustion capture: a critical review of current technologies and future directions. Energy & Fuels. https://doi.org/10.1021/acs.energyfuels.4c02513.
Ragnheidardottir, E., Sigurdardottir, H., Kristjansdottir, H., Harvey, W., 2011. Opportunities and challenges for CarbFix: an evaluation of capacities and costs for the pilot scale mineralization sequestration project at Hellisheidi, Iceland and beyond. Int. J. Greenh. Gas Control 5, 1065–1072. https://doi.org/10.1016/j.ijggc.2010.11.010.
Raj, T., Verma, S., Kumar, N., Agrawal, R., 2024. Role of woody biomass in carbon capture, circular bioeconomy, and biomanufacturing. In: Sustainable Biorefining of Woody Biomass to Biofuels and Biochemicals. Elsevier, pp. 291–318. https://doi.org/10.1016/B978-0-323-91187-0.00002-3.
Ramzan, S., Rasool, T., Bhat, R.A., Ahmad, P., Ashraf, I., Rashid, N., ul Shafiq, M., Mir, I.A., 2020. Agricultural soils a trigger to nitrous oxide: a persuasive greenhouse gas and its management. Environ. Monit. Assess. 192, 436. https://doi.org/10.1007/s10661-020-08410-2.
Rassenfoss, S., 2022. CO2 capture and storage requires challenging engineering in unfamiliar spaces. J. Petrol. Technol. 74, 44–51. https://doi.org/10.2118/0322-0044-JPT.
Ray, S., Mukherjee, A., Ghosh, U., 2024. Advancements in microbial fermentation of agro and food processing wastes for generation of biofuel. In: Solid-Gaseous Biofuels Production. Wiley, pp. 245–285. https://doi.org/10.1002/9781394204816.ch10.
Ritchie, H., 2020. Cars, Planes, Trains: where Do CO_2 Emissions from Transport Come from?.
Roy, P., Mohanty, A.K., Misra, M., 2023. Prospects of carbon capture, utilization and storage for mitigating climate change. Environmental Science: Advances 2, 409–423. https://doi.org/10.1039/D2VA00236A.
Royle, M., Chachuat, B., Xu, B., Gibson, E.A., 2024. The pathway to net zero: a chemicals perspective. RSC Sustainability 2, 1337–1349. https://doi.org/10.1039/D3SU00368J.
Sadiq, M., Chau, K.Y., Ha, N.T.T., Phan, T.T.H., Ngo, T.Q., Huy, P.Q., 2024. The impact of green finance, eco-innovation, renewable energy and carbon taxes on CO2 emissions in BRICS countries: evidence from CS ARDL estimation. Geosci. Front. 15, 101689. https://doi.org/10.1016/j.gsf.2023.101689.
Sahu, S., Kunj, P., Kaur, A., Khatri, M., Singh, G., Arya, S.K., 2024. Catalytic strategies for algal-based carbon capture and renewable energy: a review on a sustainable approach. Energy Convers. Manag. 310, 118467. https://doi.org/10.1016/j.enconman.2024.118467.
Sajna, M.S., Zavahir, S., Popelka, A., Kasak, P., Al-Sharshani, A., Onwusogh, U., Wang, M., Park, H., Han, D.S., 2023. Electrochemical system design for CO2 conversion: a comprehensive review. J. Environ. Chem. Eng. 11, 110467. https://doi.org/10.1016/j.jece.2023.110467.

Salahi, M.M., Mahmoudzadeh Andwari, A., Könnö, J., Gharehghani, A., 2022. Hydrogen and ammonia fuelled internal combustion engines, a pathway to carbon-neutral fuels future. Jultika.Oulu.Fi 2, 32–35. https://doi.org/10.55670/FPLL.FUTECH.2.2.4.
Saleh, T.A., 2022. Nanomaterials and hybrid nanocomposites for CO $_2$ capture and utilization: environmental and energy sustainability. RSC Adv. 12, 23869–23888. https://doi.org/10.1039/D2RA03242B.
Salesa, Á., Esteban, L.M., Lopez-Julian, P.L., Pérez-Benedicto, J.Á., Acero-Oliete, A., Pons-Ruiz, A., 2022. Evaluation of characteristics and building applications of multi-recycled concrete aggregates from precast concrete rejects. Materials 2022 15, 5714. https://doi.org/10.3390/MA15165714, 5714 15.
Samad, A., Saghir, H., Musawwir, A., Zulkefal, M., 2024. An intelligent system for predicting the methanol conversion rate from the direct hydrogenation of CO2 under uncertainty. In: CEMP 2023. MDPI, Basel Switzerland, p. 3. https://doi.org/10.3390/materproc2024017003.
Sanz-Cobena, A., Lassaletta, L., Aguilera, E., del Prado, A., Garnier, J., Billen, G., Iglesias, A., Sánchez, B., Guardia, G., Abalos, D., Plaza-Bonilla, D., Puigdueta-Bartolomé, I., Moral, R., Galán, E., Arriaga, H., Merino, P., Infante-Amate, J., Meijide, A., Pardo, G., Álvaro-Fuentes, J., Gilsanz, C., Báez, D., Doltra, J., González-Ubierna, S., Cayuela, M.L., Menéndez, S., Díaz-Pinés, E., Le-Noë, J., Quemada, M., Estellés, F., Calvet, S., van Grinsven, H.J.M., Westhoek, H., Sanz, M.J., Gimeno, B.S., Vallejo, A., Smith, P., 2017. Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: a review. Agric. Ecosyst. Environ. 238, 5–24. https://doi.org/10.1016/J.AGEE.2016.09.038.
Saravanan, A., Yaashikaa, P.R., Senthil Kumar, P., Vickram, A.S., Karishma, S., Kamalesh, R., Rangasamy, G., 2023a. Techno-economic and environmental sustainability prospects on biochemical conversion of agricultural and algal biomass to biofuels. J Clean Prod 414, 137749. https://doi.org/10.1016/J.JCLEPRO.2023.137749.
Saravanan, A., Senthil Kumar, P., Badawi, M., Mohanakrishna, G., Aminabhavi, T.M., 2023b. Valorization of micro-algae biomass for the development of green biorefinery: Perspectives on techno-economic analysis and the way towards sustainability. Chemical Engineering Journal 453, 139754. https://doi.org/10.1016/J.CEJ.2022.139754.
Sarkar, S., Skalicky, M., Hossain, A., Brestic, M., Saha, S., Garai, S., Ray, K., Brahmachari, K., 2020. Management of crop residues for improving input use efficiency and agricultural sustainability. Sustainability 12, 1–24. https://doi.org/10.3390/su12239808.
Sarwer, A., Hamed, S.M., Osman, A.I., Jamil, F., Al-Muhtaseb, A.H., Alhajeri, N.S., Rooney, D.W., 2022. Algal biomass valorization for biofuel production and carbon sequestration: a review. Environ. Chem. Lett. 20, 2797–2851. https://doi.org/10.1007/s10311-022-01458-1.
Seymour, K., Held, M., Stolz, B., Georges, G., Boulouchos, K., 2024. Future costs of power-to-liquid sustainable aviation fuels produced from hybrid solar PV-wind plants in Europe. Sustain. Energy Fuels 8, 811–825. https://doi.org/10.1039/D3SE00978E.
Shah, M.M.R., Liang, Y., Cheng, J.J., Daroch, M., 2016. Astaxanthin-producing green microalga Haematococcus pluvialis: from single cell to high value commercial products. Front. Plant Sci. 7. https://doi.org/10.3389/fpls.2016.00531.
Shang, W.L., Chen, J., Bi, H., Sui, Y., Chen, Y., Yu, H., 2021. Impacts of COVID-19 pandemic on user behaviors and environmental benefits of bike sharing: a big-data analysis. Appl. Energy 285, 116429. https://doi.org/10.1016/J.APENERGY.2020.116429.
Shao, B., Zhu, Y., Hu, J., Zong, Y., Xie, Z., Li, S., Du, W., Wang, M., Liu, H., Qian, F., 2024. Chemical engineering solution for carbon neutrality in cement industry: tailor a pathway from inevitable CO2 emission into syngas. Chem. Eng. J. 483, 149098. https://doi.org/10.1016/j.cej.2024.149098.
Shen, Y., Qian, L., Xu, Q., Wang, S., Chen, Y., Lu, H., Zhou, Y., Ye, J., Zhao, J., Gao, X., Zhang, S., 2025. N-doped Cu2O with the tunable Cu0 and Cu+ sites for selective CO2 electrochemical reduction to ethylene. Journal of Environmental Sciences 150, 246–253. https://doi.org/10.1016/j.jes.2024.03.012.
Shenkin, E.N., 2023. Alternatives to fossil fuel-based shipping: an overview of the sail cargo industry. https://doi.org/10.1007/978-3-031-16017-2_63.
Sievert, K., Schmidt, T.S., Steffen, B., 2024. Considering technology characteristics to project future costs of direct air capture. Joule 8, 979–999. https://doi.org/10.1016/j.joule.2024.02.005.
Sigfússon, B., Arnarson, M.þ., Snæbjörnsdóttir, S.Ó., Karlsdóttir, M.R., Aradóttir, E.S., Gunnarsson, I., 2018. Reducing emissions of carbon dioxide and hydrogen sulphide at Hellisheidi power plant in 2014-2017 and the role of CarbFix in achieving the 2040 Iceland climate goals. Energy Proc. 146, 135–145. https://doi.org/10.1016/j.egypro.2018.07.018.
Silva, R.V., de Brito, J., Dhir, R.K., 2019. Use of recycled aggregates arising from construction and demolition waste in new construction applications. J. Clean. Prod. 236, 117629. https://doi.org/10.1016/J.JCLEPRO.2019.117629.
Singh, A., 2022. Be in control of your operation - integrating real-time optimization with advanced process control for optimum energy management and optimization. In: Day 2 Tue. https://doi.org/10.2118/211256-MS. November 01, 2022, SPE.
Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Le Hoang, A., Lwasa, S., McElwee, P., Nkonya, E., Saigusa, N., Soussana, J.-F., Taboada, M.A., Manning, F.C., Nampanzira, D., Arias-Navarro, C., Vizzarri, M., House, J., Roe, S., Cowie, A., Rounsevell, M., Arneth, A., 2020. Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Glob Chang Biol 26, 1532–1575. https://doi.org/10.1111/gcb.14878.
Sobieraj, K., Stegenta-Dąbrowska, S., Luo, G., Koziel, J.A., Białowiec, A., 2022. Carbon monoxide fate in the environment as an inspiration for biorefinery industry: a review. Front. Environ. Sci. 10. https://doi.org/10.3389/fenvs.2022.822463.
Solunke, R.D., Veser, G., 2011. Integrating desulfurization with CO2-capture in chemical-looping combustion. Fuel 90, 608–617. https://doi.org/10.1016/j.fuel.2010.09.039.
Song, Z., Song, S., Zhang, W., Liu, D., Wang, Q., Wu, D., Ma, C., Feng, S., 2024. Multifunctional g-C3N4-PDI/MOF-545-NH2 photocatalyst for Enhanced CO2 reduction and aniline oxidation. Sep. Purif. Technol. 353, 128174. https://doi.org/10.1016/j.seppur.2024.128174.
Sovacool, B.K., Baum, C.M., Low, S., Roberts, C., Steinhauser, J., 2022. Climate policy for a net-zero future: ten recommendations for direct air capture. Environ. Res. Lett. 17. https://doi.org/10.1088/1748-9326/ac77a4.
Spolaore, P., Joannis-Cassan, C., Duran, E., Isambert, A., 2006. Commercial applications of microalgae. J. Biosci. Bioeng. 101, 87–96. https://doi.org/10.1263/jbb.101.87.
Sreedhar, I., Vaidhiswaran, R., Kamani, B.M., Venugopal, A., 2017. Process and engineering trends in membrane based carbon capture. Renew. Sustain. Energy Rev. 68, 659–684. https://doi.org/10.1016/j.rser.2016.10.025.
Stéphenne, K., 2014. Start-up of world's first commercial post-combustion coal fired ccs project: contribution of shell cansolv to saskpower boundary dam iccs project. Energy Proc. 63, 6106–6110. https://doi.org/10.1016/j.egypro.2014.11.642.
Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., de Courcelles, V. de R., Singh, K., Wheeler, I., Abbott, L., Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D., Lal, R., Lehmann, J., O'Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164, 80–99. https://doi.org/10.1016/j.agee.2012.10.001.
Strittmatter, C.S., Poehlein, A., Himmelbach, A., Daniel, R., Steinbüchel, A., 2023. Medium-chain-length fatty acid catabolism in Cupriavidus necator H16: transcriptome sequencing reveals differences from long-chain-length fatty acid β-oxidation and involvement of several homologous genes. Appl. Environ. Microbiol. 89. https://doi.org/10.1128/aem.01428-22.
Su, D., Herraiz, L., Lucquiaud, M., Thomson, C., Chalmers, H., 2023. Thermal integration of waste to energy plants with Post-combustion CO2 capture. Fuel 332, 126004. https://doi.org/10.1016/j.fuel.2022.126004.
Surkatti, R., Abdullatif, Y.M., Muhammad, R., Sodiq, A., Mroue, K., Al-Ansari, T., Amhamed, A.I., 2025. Comparative analysis of amine-functionalized silica for direct air capture (DAC): material characterization, performance, and thermodynamic efficiency. Sep. Purif. Technol. 354, 128641. https://doi.org/10.1016/j.seppur.2024.128641.
Tabibian, S.S., Sharifzadeh, M., 2023. Statistical and analytical investigation of methanol applications, production technologies, value-chain and economy with a special focus on renewable methanol. Renew. Sustain. Energy Rev. 179, 113281. https://doi.org/10.1016/J.RSER.2023.113281.
Tan, L., Cai, L., Fu, Y., Zhou, Z., Guan, Y., 2023. Numerical investigation of biomass and liquefied natural gas driven oxy-fuel combustion power system. Renew. Energy 208, 94–104. https://doi.org/10.1016/j.renene.2023.03.014.
Tao, H., Jia, T., Zhang, L., Li, X., Li, P., Zhou, Y., Zhai, C., 2024. Tandem effect at snowflake-like cuprous sulphide interfaces for highly selective conversion of carbon dioxide to formate by electrochemical reduction. J. Colloid Interface Sci. 655, 909–919. https://doi.org/10.1016/j.jcis.2023.11.072.
Tuinier, M.J., van Sint Annaland, M., Kramer, G.J., Kuipers, J.A.M., 2010. Cryogenic CO2 capture using dynamically operated packed beds. Chem. Eng. Sci. 65, 114–119. https://doi.org/10.1016/j.ces.2009.01.055.
UN, 2024. Affordable and Clean Energy.
Waltz, E., 2024. Microbe-made jet fuel. Nat. Biotechnol. 42, 163–166. https://doi.org/10.1038/s41587-024-02136-z.
Wang, X., Yin, W.J., Si, Y., Wang, X., Guo, X., Guo, W., Fu, Y., 2020. Conversion of CO2 to chemical feedstocks over bismuth nanosheets in situ grown on nitrogen-doped carbon. J Mater Chem A Mater 8, 19938–19945. https://doi.org/10.1039/D0TA07411J.
Wang, Z., Huang, Z., Huang, Y., Wittram, C., Zhuang, Y., Wang, S., Nie, B., 2024a. Synergy of carbon capture, waste heat recovery and hydrogen production for industrial decarbonisation. Energy Convers. Manag. 312, 118568. https://doi.org/10.1016/j.enconman.2024.118568.
Wang, C., Jiang, H., Miao, E., Wang, Y., Zhang, T., Xiao, Y., Liu, Z., Ma, J., Xiong, Z., Zhao, Y., Zhang, J., 2024b. Accelerated CO2 mineralization technology using fly ash as raw material: recent research advances. Chem. Eng. J. 488, 150676. https://doi.org/10.1016/j.cej.2024.150676.
Wang, E., Navik, R., Miao, Y., Gao, Q., Izikowitz, D., Chen, L., Li, J., 2024c. Reviewing direct air capture startups and emerging technologies. Cell Rep Phys Sci 5, 101791. https://doi.org/10.1016/j.xcrp.2024.101791.
Watson, M.J., Machado, P.G., da Silva, A.V., Saltar, Y., Ribeiro, C.O., Nascimento, C.A.O., Dowling, A.W., 2024. Sustainable aviation fuel technologies, costs, emissions, policies, and markets: a critical review. J. Clean. Prod. 449, 141472. https://doi.org/10.1016/j.jclepro.2024.141472.
Waxman, A.R., Corcoran, S., Robison, A., Leibowicz, B.D., Olmstead, S., 2021. Leveraging scale economies and policy incentives: carbon capture, utilization & storage in Gulf clusters. Energy Pol. 156, 112452. https://doi.org/10.1016/j.enpol.2021.112452.
Witte, K., 2021. Social acceptance of carbon capture and storage (Ccs) from industrial applications. Sustainability 13. https://doi.org/10.3390/su132112278.
WNA, Carbon Dioxide Emissions From Electricity, 2024. World Nuclear Asscoaition: Energy and the Environment.
Wu, Y., Zhou, C., Li, Y., Yu, Y., Zhang, Z., Wang, G., 2025. Direct Air Capture carbon dioxide by the 2D single atom solution compressor. Sep. Purif. Technol. 353, 128442. https://doi.org/10.1016/j.seppur.2024.128442.
Xin, Y., Zhang, W., Chen, F., Xing, X., Han, D., Hong, H., 2024. Integrating solar-driven biomass gasification and PV-electrolysis for sustainable fuel production:

thermodynamic performance, economic assessment, and CO2 emission analysis. Chem. Eng. J., 153941 https://doi.org/10.1016/j.cej.2024.153941.

Xu, X., Wei, Q., Xi, Z., Zhao, D., Chen, J., Wang, J., Zhang, X., Gao, H., Wang, G., 2023. Research progress of metal-organic frameworks-based materials for CO2 capture and CO2-to-alcohols conversion. Coord. Chem. Rev. 495, 215393. https://doi.org/10.1016/j.ccr.2023.215393.

Yaashikaa, P.R., Senthil Kumar, P., Saravanan, A., Karishma, S., Rangasamy, G., 2023. A biotechnological roadmap for decarbonization systems combined into bioenergy production: prelude of environmental life-cycle assessment. Chemosphere 329, 138670. https://doi.org/10.1016/J.CHEMOSPHERE.2023.138670.

Yagmur Goren, A., Erdemir, D., Dincer, I., 2024. Comprehensive review and assessment of carbon capturing methods and technologies: an environmental research. Environ. Res. 240, 117503. https://doi.org/10.1016/j.envres.2023.117503.

Yan, X., Wang, S., Chen, Z., Zhou, Y., Huang, H., Wu, J., He, T., Yang, H., Yan, L., Bao, K., Menezes, P.W., Kang, Z., 2024. Construction of coherent interface between Cu2O and CeO2 via electrochemical reconstruction for efficient carbon dioxide reduction to methane. J. Colloid Interface Sci. 673, 60–69. https://doi.org/10.1016/j.jcis.2024.05.212.

Yang, Y., Holappa, L., Saxen, H., van der Stel, J., 2024a. In: Seetharaman, S., Guthrie, R., McLean, A., Seetharaman, S., H.Y.B.T.-T, P.M, Sohn, Second E. (Eds.), Chapter 1.2 - Ironmaking. Elsevier, pp. 7–88. https://doi.org/10.1016/B978-0-323-85373-6.00001-6.

Yang, F., Xing, L., Opoku, K.N., Zhao, H., Wang, Z., Ni, R., Gao, Q., Guo, Z., Zeng, F., Yuan, A., Pan, J., 2024b. Wastes against wastes treatment: industrial silica fume derived porous solid amine adsorbent for efficient and reversible ultralow-pressure CO2 adsorption. Sep. Purif. Technol. 352, 128257. https://doi.org/10.1016/j.seppur.2024.128257.

Yuan, J.-H., Lyon, T.P., 2012. Promoting global CCS RDD& D by stronger U.S.–China collaboration. Renew. Sustain. Energy Rev. 16, 6746–6769. https://doi.org/10.1016/j.rser.2012.08.014.

Yuan, Z., Eden, M.R., Gani, R., 2016. Toward the development and deployment of large-scale carbon dioxide capture and conversion processes. Ind. Eng. Chem. Res. 55, 3383–3419. https://doi.org/10.1021/acs.iecr.5b03277.

Zanatta, M., 2023. Materials for direct air capture and integrated CO2 conversion: advancement, challenges, and prospects. ACS Materials Au 3, 576–583. https://doi.org/10.1021/acsmaterialsau.3c00061.

Zapf, F., Wallek, T., 2022. Case-study of a flowsheet simulation using deep-learning process models for multi-objective optimization of petrochemical production plants. Comput. Chem. Eng. 162, 107823. https://doi.org/10.1016/j.compchemeng.2022.107823.

Zhang, B., Tian, H., Lu, C., Dangal, S.R.S., Yang, J., Pan, S., 2017. Global manure nitrogen production and application in cropland during 1860–2014: a 5 arcmin gridded global dataset for Earth system modeling. Earth Syst. Sci. Data 9, 667–678. https://doi.org/10.5194/essd-9-667-2017.

Zhang, Z., Pan, S.Y., Li, H., Cai, J., Olabi, A.G., Anthony, E.J., Manovic, V., 2020. Recent advances in carbon dioxide utilization. Renew. Sustain. Energy Rev. 125. https://doi.org/10.1016/j.rser.2020.109799.

Zhang, J., My Pham, T.H., Gao, Z., Li, M., Ko, Y., Lombardo, L., Zhao, W., Luo, W., Züttel, A., 2023. Electrochemical CO2 reduction over copper phthalocyanine derived catalysts with enhanced selectivity for multicarbon products. ACS Catal. 13, 9326–9335. https://doi.org/10.1021/ACSCATAL.3C01439/SUPPL_FILE/CS3C01439_SI_001.PDF.

Zhang, P., Feng, K., Yan, L., Guo, Y., Gao, B., Li, J., 2024. Overlooked CO2 emissions induced by air pollution control devices in coal-fired power plants. Environmental Science and Ecotechnology 17, 100295. https://doi.org/10.1016/j.ese.2023.100295.

Zhao, Y., 2024. Research of carbon dioxide reduction in new energy applications, highlights in science. Eng. Technol. 83, 113–120. https://doi.org/10.54097/21b5jn25.

Zhou, X., Wu, Y.-S., Chen, H., Elsayed, M., Yu, W., Zhao, X., Murtaza, M., Shahzad Kamal, M., Zafar Khan, S., Al-Abdrabalnabi, R., Ren, B., 2024. Review of Carbon dioxide utilization and sequestration in depleted oil reservoirs. Renew. Sustain. Energy Rev. 202, 114646. https://doi.org/10.1016/j.rser.2024.114646.

Zhu, Q., 2019. Developments on CO2-utilization technologies. Clean Energy 3, 85–100. https://doi.org/10.1093/ce/zkz008.