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Synergistic Approach To Derive Green Fuels From Co2 And Their Mapping With Sdgs

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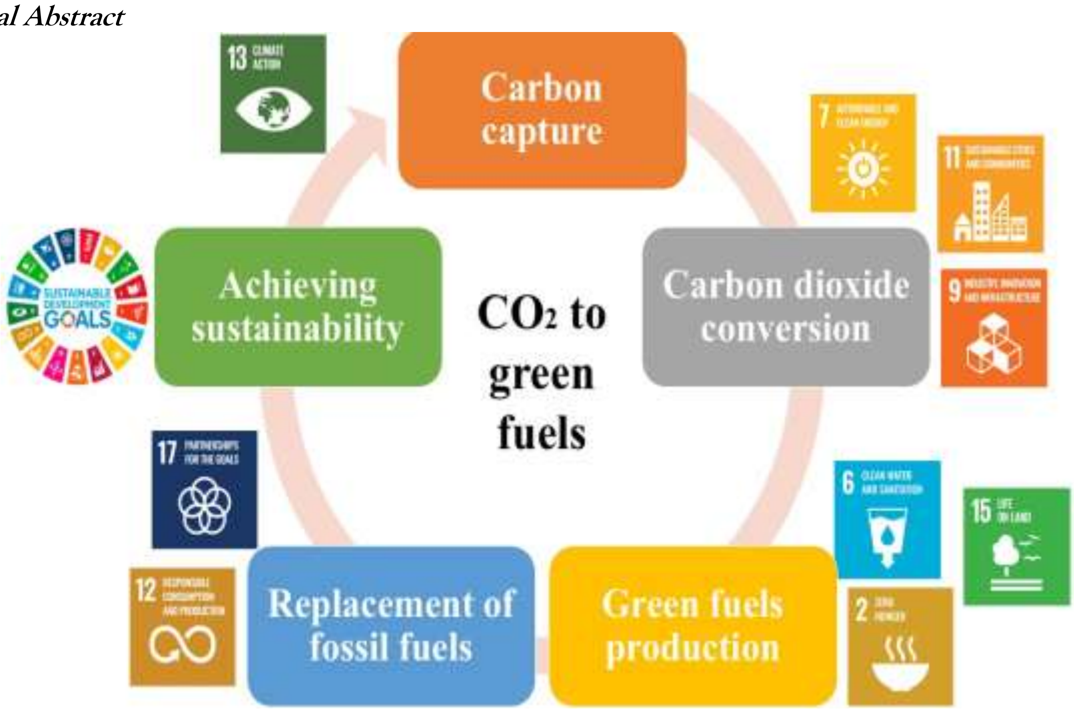
Abstract
The growing demand for sustainable energy alternatives has led to extensive research into utilizing carbon dioxide as a raw material for producing green fuels. A comprehensive and sustainable strategy combines various advanced technologies including thermocatalysis, electrocatalysis, photocatalysis and bioconversion technologies to effectively convert CO_2 into renewable energy carriers such as methane, methanol, ethanol, syngas, and long-chain hydrocarbons. By integrating these complementary techniques, this approach enhances energy efficiency, increases fuel yield, and reduces environmental impact. Significant advancements in this field include thermocatalytic hydrogenation, where CO_2 reacts with renewable hydrogen to synthesize fuels, and electrocatalytic CO_2 reduction, which uses renewable electricity to generate carbon-based energy sources. Photocatalysis capitalizes on solar energy to facilitate CO_2 reduction, while biological conversion employs genetically modified microorganisms and algae to produce biofuels. The seamless integration of these methods, coupled with renewable energy sources like solar and wind power, presents a viable pathway toward achieving carbon neutrality. This review examines recent breakthroughs in CO_2-to-fuel conversion, with a focus on catalyst innovation, process enhancement, and system integration. It also addresses key challenges associated with large-scale implementation, such as high energy consumption, catalyst degradation, and economic viability. By adopting an interdisciplinary approach, this research underscores how the convergence of advanced technologies can provide a sustainable and scalable solution for mitigating CO_2 emissions and accelerating the transition to a cleaner energy future.

Graphical Abstract



Graphical abstract

Keywords carbon capture and storage, CO_2-to-fuels, catalytic conversion, sustainable development goals, SDG mapping, green fuels

1. Introduction

Climate change and global warming are two of the most significant problems the world is now dealing with. They are brought on mainly by human activities like burning fossil fuels, deforestation, and industrial operations, which increase the amount of greenhouse gases like carbon dioxide and methane in the atmosphere. Rising sea levels, extreme weather events (such as hurricanes, floods, and heat waves), changes in ecosystems and biodiversity, and rising global temperatures are only a few of the far-reaching consequences (Zeb et al. 2017). Vulnerable groups are disproportionately impacted by these changes, particularly in places where poverty and environmental instability are already problems. International collaboration is necessary to address these issues. It entails cutting carbon emissions, switching to renewable energy, enhancing manufacturing and agricultural sustainability, safeguarding and repairing ecosystems, and getting ready for the already-occurring and unavoidable effects of climate change (Down to earth 2025). Climate change and global warming are causing a series of dire repercussions that endanger human societies and the environment. Extreme heat waves increase in frequency as temperatures rise, endangering human health and straining food and water supplies. Sea levels are increasing as a result of glacier and ice cap melting, putting coastal settlements in jeopardy and forcing millions of people to relocate. Extreme weather events like hurricanes, floods, and droughts are also becoming more intense as a result of these changes, and they have the potential to destroy livelihoods, infrastructure, and crops (World Economic Forum 2025).

Human activities involving the combustion of fossil fuels for energy, transportation, and industrial operations are the main source of CO_2 emissions. The biggest source is the energy sector, which produces heat and electricity for use in homes, businesses, and industries through the burning of coal, oil, and natural gas (Zeb et al. 2017). Due to reliance on gasoline and diesel fuels, vehicles such as cars, trucks, airplanes, and ships also contribute significantly to CO_2 emissions. Furthermore, in production operation sectors, including steel, cement, and chemical manufacturers emit significant volumes of CO_2. The issue is made worse by land-use changes and deforestation, which reduce the planet's ability to absorb and store carbon (Rhodium group 2025). Agricultural operations, especially livestock farming, also contribute to global warming since they release CO_2 through soil cultivation and livestock methane emissions, which are different yet also contribute to global warming. Since these sources collectively produce most of the CO_2 emissions caused by human activity, they are important targets for mitigating the effects of climate change. Due in major part to the growing use of fossil fuels for energy, transportation, and industrial output, CO_2 emissions have been continuously increasing globally. According to recent research, fossil fuels are the main cause of climate change, contributing almost 80% of global CO_2 emissions together with other greenhouse gas emissions (World Economic Forum 2025). The main contributors to the predicted 36.3 billion metric tons of CO_2 emissions worldwide in 2021 were industrialized and fast industrializing countries. India, the United States, and China are the top emitters. China is the world's greatest emitter of CO_2, accounting for roughly 28% of emissions due to its fast industrialization and strong reliance on coal for electricity generation. The United States comes in second, accounting for around 15% of world emissions, mostly from transportation and energy use. Due in great part to its use of coal for electricity and industrial purposes, India, an economy that is expanding quickly, is also a significant emitter, accounting for around 7% of world emissions. Russia, Japan, and the European Union are other significant contributors (Rhodium group 2025). List of major CO_2s emitting sources has been discussed in the following table 1.

Table 1: List of major CO_2s emitting sectors (WRI 2025; USEPA 2025; Terrascope 2025)

Source	CO_2 emitting sectors
Fossil fuel combustion in transport sector	Road (16%)
	Ship (2.5%)
	Air (2.55%)
	Rail and pipeline (0.8%)
Industry Processes	Cement (4.03%)
	Iron and steel (4.98%)

	Unallocated fuel burning (2.82%)
Electricity and heat	Residential building (14.67%)
	Commercial building (8.88%)
Agriculture	Agriculture (1.21%)
	Fisheries (1.07%)
Chemicals	2.42%
Land-use change	Burning (2.42%)
	Crop land (1.88%)
	Forest land (2.96%)
Manufacturing and construction	7.27%
Other industry	6.72%

Coal, oil, and natural gas are the three fossil fuels that still account for 80–85% of the world's energy consumption. Oil continues to be the primary energy source, especially in the transportation industry, where it powers automobiles, trucks, ships, and aircraft (Zeb et al. 2017). Additionally, it is essential for industrial operations as well as the manufacturing of chemicals and polymers. Despite its negative effects on the environment, coal is still a significant energy source, especially in nations like China and India where it is mostly utilized for industrial and electricity production. Although natural gas emits fewer carbon emissions than coal and oil, its use has been growing quickly, particularly for heating and power generation. Currently, it accounts for almost 25% of the world's energy consumption. Fossil fuels continue to dominate the global energy mix despite the rise of renewable energy sources like wind, solar, and hydropower (World Economic Forum 2025). This is especially true in industries like heavy industry and transportation, where the switch to cleaner alternatives is still difficult. There is an urgent need to switch to cleaner, more sustainable energy sources because of the continued reliance on fossil fuels, which is a major contributor to global CO_2 emissions and climate change.

Globally, CO_2 emissions have a significant influence on wildlife, people, and the environment. Industrial operations greatly contribute to climate change by releasing massive amounts of carbon dioxide into the atmosphere, which changes weather patterns and raises global temperatures (Down to earth 2025). Ecosystems are directly impacted by this, as changing climate conditions disturb habitats and make it harder for many plant and animal species to survive. The consequences of climate change, including fires, droughts, and ocean acidification, are posing a growing threat to forests, wetlands, and coral reefs all of which are essential for biodiversity and carbon storage. Industrial CO_2 emissions cause a number of health concerns for people, such as respiratory disorders brought on by poor air quality and heat-related ailments brought on by increased temperatures. Due to unexpected crop yields and water shortages brought on by changing climates, communities that depend on agriculture are also at risk. Because both terrestrial and marine species are driven from their natural habitats, industrial CO_2 emissions have a cascading effect on global food chains and result in a loss of biodiversity.

A sustainable substitute for fossil fuels, which are a major contributor to climate change, renewable energy is essential in lowering global CO_2 emissions. Renewable energy sources including solar, wind, hydropower, and geothermal power produce electricity without releasing greenhouse gases, in contrast to coal, oil, and natural gas. One of the biggest sources of CO_2 emissions worldwide is the electricity sector, whose carbon emissions can be significantly reduced by switching to renewable energy. Furthermore, renewable energy systems are getting more affordable, which increases their accessibility on a global scale. Renewable energy helps lessen the consequences of global warming, enhance air quality, and advance energy security by lowering reliance on fossil fuels, which account for the bulk of CO_2 emissions worldwide. Additionally, increasing the usage of renewables fosters the advancement of green technologies, generates employment, and advances a healthier, cleaner environment. Meeting global climate targets and averting the worst effects of climate change require accelerating the transition to renewable energy.

Carbon capture and utilization (CCU), the process of turning CO_2 into green fuels, is a creative way to combat climate change and generate sustainable energy. Through the use of renewable energy sources, CO_2 emissions from sources such as power plants or the environment itself are captured and transformed into useful fuels like ethanol, methane, or synthetic gasoline. These green fuels are produced from CO_2 using technologies including electrolysis, artificial photosynthesis, and biological processes. Reusing CO_2 offers a potential means of producing carbon-neutral or even carbon-negative fuels in addition to assisting in the reduction of greenhouse gas concentrations in the environment. By using these green fuels in already-existing infrastructure, including cars and power plants, overall emissions can be decreased and reliance on fossil fuels can be lessened. Although it is still in its infancy, the conversion of CO_2 to green fuels has the potential to be a crucial element of a low-carbon economy in the future, bridging the gap between the present dependence on fossil fuels and a completely sustainable energy system.

Utilizing green fuels made from CO_2 conversion offers a viable way to both fulfill the energy demands of the world's expanding population and lessen the effects of climate change. This technique can produce a closed-loop system that lowers the amount of greenhouse gases in the environment by absorbing excess CO_2 emissions from industrial sources and turning them into fuels that can be used, such as hydrogen, ethanol, or synthetic methane. Because they are carbon-neutral or even carbon-negative if the CO_2 used in their production is removed from the atmosphere, green fuels made from CO_2 conversion have the potential to replace fossil fuels in a number of industries, including transportation, power generation, and industrial activities. This lessens dependency on nonrenewable resources and helps to cut CO_2 emissions worldwide. Additionally, the growth and expansion of these green fuel technologies may promote the shift to a more sustainable, circular economy, stimulate new sectors, and provide employment.

By using green fuels made from CO_2 conversion, these technologies have the potential to be extremely important in decarbonizing sectors like heavy industry, shipping, and aviation that are otherwise challenging to electrify. Synthetic fuels created from CO_2, such as e-kerosene for airplanes or e-diesel for trucks, could drastically cut emissions from industries that rely heavily on fossil fuels. Figure 1 shows various chemical products obtained from CO_2 conversion. Green fuel production can be further integrated into sustainable energy systems by utilizing renewable energy to power CO_2 conversion operations. This will increase the adoption of clean energy sources and lessen reliance on the extraction of fossil fuels. Green fuels made from CO_2 conversion can also be used as a renewable energy storage medium. Converting excess energy into stable, transportable fuels can help balance supply and demand because renewable energy sources like sun and wind are sporadic. This ensures that energy flows continuously even in the absence of renewable sources. Because of their adaptability, CO_2-derived fuels are a desirable option for energy security, especially in areas where access to large-scale storage technology is restricted. Widespread use of CO_2 conversion technology may offer advantages for the environment that go beyond energy. These procedures have the potential to lower the total amount of CO_2 in the atmosphere by absorbing and reusing it, which could support efforts to stabilize the climate and eventually contribute to global cooling. Even though there are still issues with scalability, infrastructure development, and high energy costs, further development of CO_2-to-fuel technologies may open the door to a cleaner, more sustainable energy future.

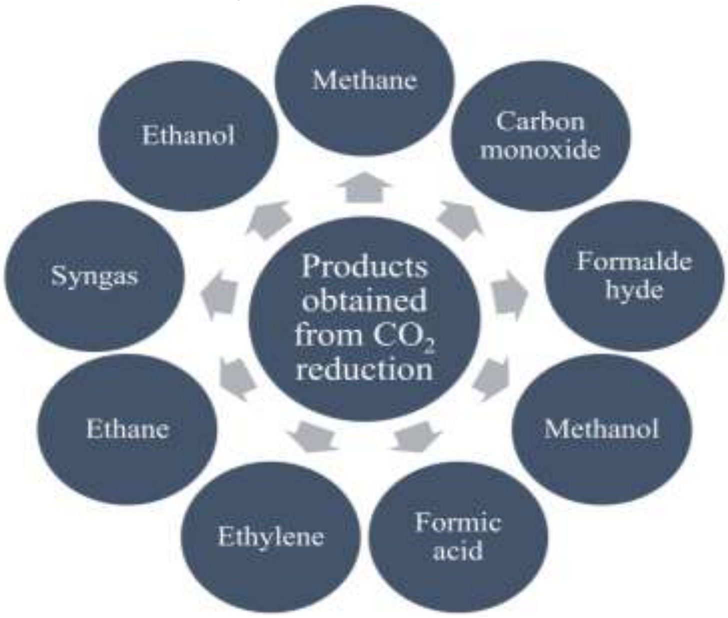


Fig 1: Chemical products obtained from CO_2 conversion

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2. CO_2 conversion technologies

2.1 Carbon capture storage and utilization (CCSU) technologies

For converting CO_2 into green fuels, first and foremost demanding and commercially applied technology is carbon capture storage and utilization technologies. The technology deals with capturing carbon dioxide from source such as power plants and storing them underground or deep-sea burial or utilizing captured carbon in form of raw materials or fuels. The carbon capture technologies involve pre-combustion, post-combustion and oxy-combustion technologies. Techniques like absorption, adsorption, cryogenic distillation and membrane gas separation are some of the commercially applied CO_2 separation methods (Gautam et al. 2025).
This approach combines advanced capture techniques, secure storage options, and multiple utilization pathways, forming a closed-loop carbon cycle. When paired with renewable hydrogen or bio-based reducing agents, captured CO_2 can be transformed into clean synthetic fuels including methanol, methane, and liquid hydrocarbons (Saleh and Hassan 2023). Despite being abundant, carbon dioxide is extremely challenging to activate due to its thermodynamic stability, complete oxidation state, and chemical inertness. One of the key limitations in its utilization for fuel synthesis lies in the tendency of CO_2 hydrogenation processes to produce mainly short-chain hydrocarbons, which are less desirable compared to long-chain hydrocarbons. Consequently, much of the research to date has focused on stepwise hydrogenation of CO_2 to simpler products such as methane (CH_4), formic acid (HCOOH), methanol (CH_3OH), and C_2 - C_4 olefins, rather than directly obtaining heavier hydrocarbon liquids (C_5 and above), which are more suitable for use as fuels (Chen et al. 2016).

There are two main pathways for producing hydrocarbon liquids from CO_2:

- **Indirect Route** – This involves first converting CO_2 into intermediates like carbon monoxide or methanol, which are then further processed into liquid hydrocarbons.
- **Direct Hydrogenation Route** – In this method, CO_2 is initially reduced to CO via the reverse water–gas shift (RWGS) reaction, followed by Fischer–Tropsch synthesis (FTS) to yield long-chain hydrocarbons. This route is generally considered more energy-efficient and environmentally favorable, as it reduces the number of processing steps and overall energy consumption. The reactions involved in these transformations are critical to the generation of hydrocarbon fuels from captured CO_2.

Addressing climate change demands urgent action, and reducing greenhouse gas emissions is a global priority. Transitioning to carbon-neutral or carbon-negative energy systems offers a viable solution. In this context, CO_2-derived fuels and materials represent a promising opportunity, although significant technical and economic challenges still need to be addressed. Transforming CO_2 into renewable fuels and high-value chemicals stands out as a strategic approach to mitigate emissions while supporting sustainable energy development (Ishaq and Crawford 2023). CCSU offers a dual advantage by lowering greenhouse gas emissions while unlocking avenues for economic growth. Its implementation can be economically viable, particularly when the captured CO_2 is repurposed to generate value-added products. Nevertheless, the current deployment of CCSU technologies remains relatively small in scale, and their practicality may vary across different sectors and industrial processes.

2.2 Catalytic conversion technologies

Catalytic conversion technology for CO_2-to-green fuels employs catalysts to enhance chemical reactions, facilitating the transformation of carbon dioxide into useful fuels like methane, methanol, ethanol, and synthetic hydrocarbons. These conversions are often aided by temperature, electrochemical reactions, photochemical reactions, plasma-activated reactions or a combination of two or more among them. Thus, catalytic conversion technologies can be broadly classified as shown in figure 2.

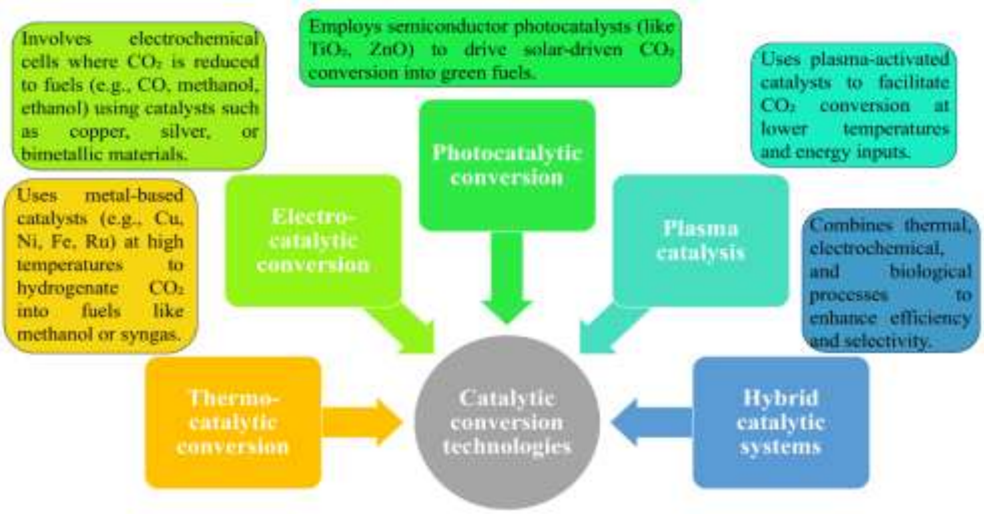

Fig 2: classification of various catalytic conversion technologies

2.2.1 Thermo-catalytic conversion technology

Thermo-catalytic conversion technology is an advanced approach for transforming carbon dioxide into sustainable green fuels, including methane, methanol, syngas (a mixture of CO and H_2), and liquid hydrocarbons. This process operates under high-temperature conditions with the aid of catalysts, enabling the efficient conversion of CO_2 into valuable energy carriers. A critical component of this method is hydrogenation, which typically relies on renewable hydrogen derived from water electrolysis or biomass gasification. By integrating thermos-catalytic processes with renewable energy sources, this technology presents a viable pathway for reducing carbon emissions while supporting energy sustainability.

Catalysts used are equally essential in thermo-catalytic CO_2 conversion, as they influence reaction rates, product selectivity, and overall efficiency of the process. Among the most widely used catalysts, nickel-based catalysts (Ni) are favored for CO_2 methanation and dry reforming of methane due to their affordability and strong catalytic activity (Gao et al. 2021; Kim 2024; Len and Luque 2023). Copper-based catalysts (Cu) play a significant role in methanol synthesis, offering high selectivity and thermal stability (Ahmad et al. 2023; Duma 2022), while iron-based catalysts (Fe) are frequently employed in Fischer-Tropsch synthesis and the reverse water-gas shift (RWGS) reaction for hydrocarbon production (Jia et al. 2024; Wang et al. 2024). Ruthenium-based catalysts (Ru) though it is an expensive alternate but exhibit superior catalytic stability and good efficiency in CO_2 hydrogenation and deriving fuels like methane (Vieira et al. 2023; Castellano 2022). Additionally, cobalt-based catalysts (Co) are commonly applied in Fischer-Tropsch processes to produce synthetic fuels with good yields. (He et al. 2024; Kandathil et al. 2024). Recent advancements have introduced perovskite catalysts, which offer tunable properties to enhance catalytic performance. Furthermore, bimetallic and alloy catalysts such as Cu-Zn, Ni-Co, and Fe-Mn have demonstrated improved reaction rates, enhanced stability, and reduced deactivation, making them promising candidates for large-scale applications. Table 2 summarizes various metal-based catalysts along with their applications, advantages and their challenges.

Table 2: summary of various metal-based catalysts along with their applications, advantages and their challenges

Catalysts	Application	Advantages	Challenges
Ni-based	Methanation, dry reforming of methane (for production of syngas from methane)	Low cost, high activity	Carbon deposition
Cu-based	Methanol synthesis	High selectivity, stability	Limited thermal resistance
Fe-based	Fischer-Tropsch Synthesis (Long-chain hydrocarbons for synthetic fuels), Reverse Water-	Abundant, versatile	Requires promoters

	Gas Shift (RWGS) Reaction (Precursor for Fischer-Tropsch Synthesis)		
Ru-based	Hydrogenation	High efficiency, stability	High cost
Co-based	Fischer-Tropsch	High hydrocarbon yield	Catalyst sintering

Despite its potential, thermocatalytic CO_2 conversion faces several challenges that must be addressed for widespread adoption. One of the primary concerns is the high energy demand required to maintain elevated reaction temperatures, which impacts the overall efficiency of the process. Additionally, catalyst deactivation, caused by carbon deposition and sintering, reduces the long-term effectiveness of catalysts, necessitating the development of more durable materials. Another major hurdle is the availability of sustainable hydrogen, as large-scale hydrogen production remains costly and energy-intensive. Lastly, economic viability remains a key issue, as scaling up catalytic CO_2 conversion processes while maintaining cost efficiency continues to be a challenge.
By overcoming these technical and economic barriers, thermocatalytic CO_2 conversion has the potential to play a crucial role in reducing greenhouse gas emissions and advancing the transition toward a more sustainable energy system.

2.2.2 Electrocatalytic conversion technologies

Electrocatalytic reduction of carbon dioxide has become a leading sustainable method for converting CO_2 into value-added fuels and chemicals by utilizing electricity, preferably derived from renewables such as solar or wind power. This technique serves as a cleaner alternative to conventional fuel production and aligns with carbon circularity by turning emissions into useful products. In an electrochemical system, CO_2 is reduced at the cathode while water is oxidized at the anode, releasing oxygen as shown in equation 1. The performance of the carbon dioxide conversion largely depends on the type of electrocatalyst used, as it determines product yield and selectivity.

$$CO_2 + nH^+ + ne^- \rightarrow products\ (CH_4, CH_3OH, C_2H_5OH, HCOOH) \quad (1)$$

For instance, copper is unique in enabling carbon–carbon coupling to produce multi-carbon compounds like ethylene, ethanol, and propanol, though controlling product distribution remains complex (Malik et al. 2017; Zhang et al. 2022). Metals like silver and gold are highly selective for carbon monoxide formation and operate at low overpotentials (Zhao et al. 2018; Elseman and Abdelbasir 2024; Beheshti et al. 2023). Studies shows that tin and bismuth favor the production of formate or formic acid (Ding et al. 2023; Liang et al. 2023). Additionally, nickel and iron have shown effectiveness in syngas production, especially when structured as single-atom catalysts (SACs) for enhanced durability (Sanjuán et al. 2024; Abdel-Mageed et al. 2021). Advances in cell design, such as flow cells and membrane electrode assemblies (MEAs), have addressed issues of scalability and efficiency, enabling higher reaction rates and integration into pilot systems. These technologies are also well-suited for pairing with renewable energy systems, offering the possibility of on-site fuel production with minimal carbon impact. Innovations in catalyst architecture such as the use of nanostructures, single-atom designs, and metal–organic frameworks have significantly improved reaction performance (Zhao et al. 2018). However, challenges such as poor selectivity, catalyst degradation, and energy-intensive operation still hinder widespread adoption (Zhao et al. 2018). Looking forward, developments in artificial intelligence-assisted catalyst discovery, in situ diagnostic techniques, and hybrid systems like photo-electrocatalysis could transform the field. Policy incentives and infrastructure investment will also be critical to drive commercial viability and large-scale implementation of this promising green technology.

2.2.3 Photocatalytic conversion technologies

Photocatalysis triggers chemical reactions by subjecting a semiconductor photocatalyst to visible or ultraviolet light. This process consists of three main stages: light absorption, charge separation, and product formation. Initially, photons are absorbed, leading to charge separation, where electrons transition from the valence band to the conduction band, generating positively charged holes. Finally, the formation of products takes place through a redox reaction. The mechanism of CO_2 photoreduction can produce various products, including CO, CH_4, CH_3OH, and HCOOH, as well as C_2 compounds like C_2H_2 and C_2H_5OH. The specific products formed

depend on the type of catalyst and the reaction conditions (Zhang et al. 2018). Different photocatalysts, such as metals, metal oxides, and metal–organic frameworks (MOFs), have been utilized for this process (Li et al. 2021). One of the pioneering studies on the photocatalytic conversion of CO_2 to CH_3OH was conducted by Solymosi and Tombácz in early 1990s. Their research significantly contributed to this field by analyzing the influence of catalysts and doping on CO_2 reduction products. They found that 1% $Rh/TiO_2/2\% WO_3$ exhibited enhanced CH_3OH selectivity, whereas TiO_2 and $TiO_2/0.1\% WO_3$ produced no CH_3OH (Solymosi and Tombácz 1994). Since then, extensive studies have focused on using TiO_2 for photocatalytic CO_2 reduction under both visible and UV light, beginning with pristine TiO_2 and later exploring its combination with various materials to evaluate the effects of metal doping. Various catalyst and solutions have been reviewed along with numerous irradiating sources varying from visible to UV with varying time duration and obtained yield for CH_3OH from CO_2 (Chebbi et al. 2023).
Producing green fuel like methanol can also be accomplished by photocatalytic partial oxidation of methane. A notable early study on the photoconversion of CH_4 to CH_3OH was carried out by Ogura and Kataoka in 1988 where the research involved a reaction between water vapor and CH_4 under standard atmospheric pressure. Upon photon exposure, water generates hydroxyl radicals ($^{\cdot}OH$), which then interact with CH_4 to form methyl radicals ($^{\cdot}CH_3$). In the final step, these methyl radicals react with water to produce CH_3OH as mentioned in equations 2 – 5 (Ogura and Kataoka 1988). TiO_2 has been widely studied as a promising catalyst for the photo-partial oxidation of CH_4 due to its high stability and strong photocatalytic activity. Other catalysts, including WO_3, Bi_2WO_6, and ZnO, have also been explored. The photocatalytic efficiency of these materials can be enhanced through metal ion doping or surface modifications.

$$H_2O + hv \rightarrow H_2 + \frac{1}{2}O_2 \quad (2)$$
$$H_2O + hv \rightarrow \frac{1}{2}H_2 + \cdot OH \quad (3)$$
$$CH_4 + \cdot OH \rightarrow \cdot CH_3 + H_2O \quad (4)$$
$$CH_3 + H_2O \rightarrow CH_3OH + \frac{1}{2}H_2 \quad (5)$$

Photocatalytic conversion technologies also aid in reducing CO_2 to form formic acid. It can be produced through a photocatalytic reaction of CO_2 in the presence of water and a photocatalyst. In late 1980s, pioneering research was conducted to derive HCOOH from CO_2 using metal sulphide semiconductors in presence of hydrogen sulphide. Rate of photocatalysis process was investigated to be increased with the presence of H_2S (Aliwi and Al-Jubori 1989). In past few years, many studies showcased the use of various metal oxides, metal-based metal organic framework, binuclear complex as well as recycled solid catalysts being employed to obtain HCOOH from CO_2 under varying operating conditions (Maeda et al. 2013; Nakada et al. 2015; Omadoko et al. 2020; Zhang et al. 2021; Mori et al. 2021).
Although photocatalytic conversion of CO_2 to green fuels is an advanced and promising technology, but advancing the large-scale photoreduction of CO_2 and evaluating the viability of photoreactors necessitate careful assessment of multiple factors, including light source availability, process control, energy consumption, automation, stability of catalyst, maintenance requirements of the process, environmental impacts of catalyst fouling or disposal and most importantly cost of process. Additionally, a thorough understanding of reaction kinetics and effective mass transfer is crucial, as these aspects significantly impact both process efficiency and the final product yield.

2.2.4 Plasma-catalytic conversion technologies

Plasma-catalytic conversion of carbon dioxide integrates non-thermal plasma (NTP) with solid catalysts to effectively break down the chemically stable CO_2 molecule and convert it into valuable products like carbon monoxide (CO), methane (CH_4), methanol (CH_3OH), and syngas ($CO + H_2$). This hybrid approach harnesses the benefits of plasma especially the generation of highly energetic electrons and reactive species at near-room temperatures together with the selectivity and stability offered by catalysts, resulting in improved conversion performance and enhanced energy efficiency (Puliyalil et al. 2018).

In NTP systems, electrical energy is utilized to accelerate electrons to high energies (1–10 electronvolts) without significantly raising the overall gas temperature. These fast electrons interact with CO_2 and other gas molecules, initiating various plasma-induced processes mainly molecular dissociation (equation 6) and excitation and ionization (equation 7 and 8).

$$e^- + CO_2 \rightarrow CO + O + e^- \quad (6)$$

$$e^- + CO_2 \rightarrow CO_2^* + e^- \quad (7)$$

$$e^- + CO_2 \rightarrow CO_2^+ + 2e^- \quad (8)$$

These plasma-generated species such as excited CO_2 (CO_2*), oxygen atoms, CO molecules, and reactive radicals, interact with the catalyst's surface, promoting higher product selectivity and yields at temperatures below 300°C. This is notably lower than traditional thermocatalytic processes, which generally require temperatures above 600°C (Rao et al. 2024).

Plasma-catalytic systems can drive these thermodynamically demanding or endothermic reactions at reduced temperatures by utilizing vibrationally excited species and radical mechanisms, thus offering a more energy-efficient pathway for CO_2 conversion into green fuels. Some of the key reactions which are taking place are dry reforming of methane (DRM) (equation 9), hydrogenation of CO_2 or methanation (equation 10) and methanol formation (equation 11).

$$CO_2 + CH_4 \rightarrow 2CO + 2H_2 \quad (\Delta H^\circ = +247\ kJ/mol) \quad (9)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (\Delta H^\circ = -165\ kJ/mol) \quad (10)$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O\ (\Delta H^\circ = -49.5\ kJ/mol) \quad (11)$$

The choice of catalyst plays a fundamental role in determining product selectivity and optimizing energy efficiency in plasma-catalytic CO_2 conversion systems. Among the commonly utilized materials, nickel-based catalysts are noted for their high reactivity in both DRM and methanation processes, though they are prone to deactivation due to carbon buildup (Da Costa et al. 2021; Ullah et al. 2023). Copper/zinc oxide supported on alumina (Cu/ZnO–Al_2O_3) is extensively applied in methanol production, and its performance is significantly enhanced by the presence of plasma-generated intermediates (Bagherzadeh et al. 2022). Perovskite-type oxides, such as $LaNiO_3$, exhibit superior redox properties and oxygen ion mobility, making them particularly suitable for use in plasma-based conversion system (Liu et al. 2020). Zeolites and metal–organic frameworks (MOFs) provide adjustable porosity and acidic or basic functional sites which help in stabilizing reactive intermediates during conversion (Vakili et al. 2020; Hosseini 2025). Moreover, single-atom catalysts (SACs) are gaining attention for their exceptional selectivity and durability under plasma conditions (Ye et al. 2024). Catalysts in plasma-assisted systems enhance reaction pathways by offering active sites for the adsorption of feed gases like CO_2, CH_4, and H_2, and by promoting the conversion of plasma-activated radicals into target molecules through controlled surface reactions.

Several reactor configurations are used to achieve the synergistic effects between plasma and catalysts. The dielectric barrier discharge (DBD) reactor is the most widely implemented due to its ability to generate uniform non-thermal plasma at atmospheric pressure by using insulating barriers to prevent electrical arcing. Microwave plasma reactors provide high electron densities, facilitating effective conversion when used alongside catalytic materials such as metals and MOFs, particularly for producing methanol and hydrocarbons. Gliding arc reactors (GARs) are capable of handling higher power inputs and are better suited for industrial-scale synthesis of fuels. The packed bed reactor design integrates catalysts either directly in the plasma zone (in situ) or downstream (post-plasma) thereby allowing for enhanced gas–surface interactions as well as volumetric reactions (Ashford and Tu 2017; Shao et al. 2025). Table 3 highlights performance matrix for various catalysts system and reactor combination.

Table 3: performance matrix for various catalysts system and reactor combination

Catalyst system	Reaction	% CO_2 conversion	% Product selectivity	Energy efficiency (g/kWh)
Ni/Al_2O_3 + DBD	DRM	~40	CO/H2 = 1:1	~20
Cu/ZnO + Microwave Plasma	Methanol Synthesis	~30	CH3OH ~80	~25
$LaNiO_3$/Zeolite + DBD	Syngas Production	~35	CO ~75	~18
Ag-Zn/ZSM-5 + DBD	CO_2 to CH_4	~45	CH4 ~70	~22
	CO_2 to CH_3OH		CH3OH ~20	

Plasma-catalytic systems, being entirely electrically driven, are well-suited for integration with renewable energy sources like solar energy and wind energy. Their essential ability to operate under fluctuating power inputs makes them ideal for decentralized and modular setups. This compatibility supports on-site fuel production in locations with high CO_2 emissions such as flue gas outlets or biogas plants (Ashford and Tu 2017).
Despite promising developments, several challenges persist. Plasma systems currently lag behind thermocatalytic methods in energy efficiency, largely due to energy dissipation during plasma generation. Improvements in reactor configurations and catalyst–plasma coupling are necessary to reduce these losses. Additionally, product separation poses a challenge due to the formation of mixed output streams (Shao et al. 2025). Catalyst deactivation, often caused by sintering or carbon fouling under plasma conditions is another issue requiring long-term solutions. From a real-world perspective, scaling up plasma reactors in a cost-effective manner remains an ongoing engineering challenge. Therefore, future advancements are expected to focus on enhancing plasma–catalyst synergy through in-situ diagnostics such as optical emission spectroscopy, which can reveal the behavior of transient species and guide rational catalyst design. There is growing interest in hybrid plasma systems that integrate electrocatalysis, photocatalysis, or thermocatalysis to enable multi-step CO_2 upgrading. Furthermore, artificial intelligence (AI) and machine learning are increasingly being employed to predict catalyst performance and active site behavior under plasma exposure. Finally, comprehensive lifecycle assessments (LCA) will be vital for evaluating both the environmental benefits and the economic feasibility of deploying these technologies at commercial scale.

2.2.5 Hybrid catalytic conversion technologies

Hybrid catalytic systems combine two or more catalytic techniques such as thermocatalysis, electrocatalysis, photocatalysis, and plasma catalysis to overcome the limitations of individual methods and achieve higher efficiency, selectivity, and scalability in CO_2 conversion. These systems leverage the complementary advantages of each approach (e.g., high selectivity of photocatalysis, high throughput of thermocatalysis, and mild conditions of electrocatalysis) to produce fuels such as methane (CH_4), methanol (CH_3OH), ethanol (C_2H_5OH), syngas (CO + H_2), and long-chain hydrocarbons (Aresta and Dibenedetto 2024).
Hybrid systems operate by sequential or simultaneous activation of CO_2 using multiple energy inputs (e.g., thermal + electrical + solar), allowing for reaction pathways that would otherwise be kinetically or thermodynamically limited. Hybrid systems are ideally suited for integration with solar PV, wind, and waste heat sources. Their modular and flexible operation allows them to adapt to fluctuating energy supply. Coupling with carbon capture from flue gas or biogas systems enables on-site fuel production and carbon circularity.

2.3 Bio conversion technologies

Bio-conversion technologies for transforming CO_2 into green fuels have emerged as promising sustainable alternatives to fossil fuels. These approaches rely on biological processes, including microbial and enzymatic pathways, to convert carbon dioxide into renewable energy sources such as methane, methanol, ethanol, and other hydrocarbons. Engineered microorganisms, algae, and biocatalysts are commonly employed to enhance CO_2 fixation and conversion under controlled environments (Carmona-Martínez et al. 2024; Sharma et al. 2024). Figure 3 shows various bioconversion technologies to drive green fuels from CO_2.

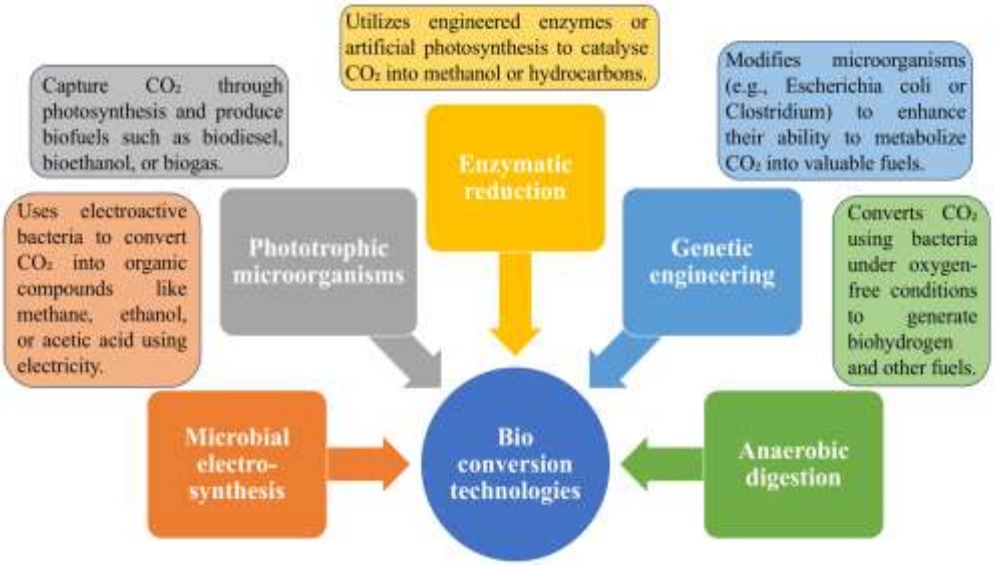

Fig 3: bioconversion technologies to drive green fuels from CO_2

Microbial Electrosynthesis (MES) involves the use of electroactive microorganisms that can convert carbon dioxide into valuable fuels and chemicals by drawing electrons from a cathode. A small electric current supplies electrons to microbes via electrodes, promoting the biochemical reduction of CO_2 (Fang et al. 2022). This technique combines green electricity with microbial activity, enabling CO_2 fixation under standard environmental conditions (Ibrahim et al. 2023). *Sporomusa ovata*, *Clostridium ljungdahlii* are some of the common microbial species which are investigated for the production of acetate, methane, ethanol and butyrate from carbon dioxide via MES technology (Jin et al. 2024).
Phototrophic Microorganisms includes microalgae and cyanobacteria that can capture sunlight and convert CO_2 into organic materials through natural photosynthetic processes. These organisms harness solar energy to transform CO_2 and water into biomass and energy-dense compounds. Gene editing tools like clustered regularly interspaced short palindromic repeats (CRISPR) and metabolic modifications are applied to increase lipid or hydrogen yield. Direct use of sunlight and compatibility with nutrient-rich waste streams and CO_2-laden gases. Lipids (which can be processed into biodiesel), hydrogen, ethanol, and sugars are some of the common green fuels obtained from carbon dioxide through phototrophic microbes (Pekkoh et al. 2024; Gnanasekaran et al. 2023).
Enzymatic CO_2 conversion includes purified enzymes or enzyme-based systems that can catalyze the transformation of CO_2 into fuels, often using cofactors or synthetic electron donors (Ünlü et al. 2021). Notable biocatalysts include formate dehydrogenase which produces formate/formic acid, carbon monoxide dehydrogenase which produces carbon monoxide and methanol dehydrogenase which produces methanol. These conversions operate under mild conditions and are sought to deliver high product selectivity (Bernhardsgrütter et al. 2021).
Engineered microorganisms are microbial strains that are genetically modified to increase CO_2 fixation and redirect carbon flow toward the production of specific fuels. Synthetic biology and CRISPR-Cas technologies are the techniques used in it. The method improves CO_2 assimilation, eliminate side-pathways, and boost resilience to fuel byproducts. Studies shows application of customized *E. coli* strains for generating isobutanol and engineered *Ralstonia eutropha* for producing biofuels and bioplastics (Woo 2017).
Anaerobic digestion with CO_2 utilization is a microbial consortium under oxygen-free conditions breaks down organic substrates, with CO_2 serving as a secondary input or electron acceptor. Biogas (primarily methane) and short-chain fatty acids are the most conventional products obtained. Methanogenic archaea such as *Methanobacterium* and *Methanosarcina* are commonly involved microbes for anaerobic digestion process. Studies shows that introducing CO_2 and hydrogen together to enhance methane production via hydrogenotrophic pathway acts as process enhancement way for anaerobic digestion (Bajón Fernández et al. 2017).

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These biological CO_2 conversion technologies provide sustainable, low-emission routes for generating alternative fuels efficiently utilize carbon-rich waste streams, renewable energy, and wastewater. Bioconversion technologies for converting CO_2 into green fuels support circular economy models and contribute to SDGs, including SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), SDG 12 (responsible consumption and production), and SDG 13 (climate action).

3. Integrating various technologies with circularity and mapping with SDGs

The growing urgency to address climate change and achieve a sustainable energy future has accelerated the development of innovative carbon management strategies. Integrating CCSU with advanced catalytic conversion methods including thermocatalytic, electrocatalytic, photocatalytic, and plasma-catalytic technologies alongside emerging bioconversion platforms such as microbial electrosynthesis, enzymatic CO_2 reduction, and genetically engineered microbes, offers a multifaceted solution for transforming CO_2 emissions into valuable green fuels. These integrated pathways not only mitigate greenhouse gas emissions but also support the principles of a circular economy by recycling carbon into renewable energy carriers. By aligning technological innovation with sustainability goals, this approach directly contributes to several UN SDGs. Table 4 highlights applied technologies for deriving green fuels from CO_2 and their mapping with SDGs.

Table 4: Mapping SDGs with various technologies for deriving green fuels from CO_2

Applied technology	Technology description	SDGs aligned	Mapping justification and impact
CCSU	Captures CO_2 emissions from industrial processes/ ambient air, stores or converts into fuels	SDG 13: climate action SDG 9: industry, innovation and infrastructure SDG 12: responsible consumption & production	- Reduces GHG emissions from heavy industry - Enables net-zero pathways - Promotes industrial decarbonization
Thermocatalytic Conversion	Uses high temperature heat and catalysts to convert CO_2 + H_2 into methanol, methane, and synthetic fuels	SDG 7: affordable and clean energy SDG 9: industry, innovation and infrastructure SDG 13: climate action	- Produces clean, storable fuels from waste CO_2 - Can be integrated with renewable hydrogen systems - Drives innovation in green fuel infrastructure
Electrocatalytic Conversion	Uses electricity (preferably from renewables) to reduce CO_2 to CO, formic acid, methanol, ethanol	SDG 7: affordable and clean energy SDG 13: climate action SDG 11: sustainable cities and communities	- Converts excess renewable power into fuels - Enables decentralized, clean fuel production
Photocatalytic Conversion	Uses solar energy and catalysts to convert CO_2 and H_2O into hydrocarbons or alcohols	SDG 7: affordable and clean energy SDG 13: climate action SDG 15: life on land	- Utilizes sunlight as an energy source - Lowers carbon footprint of fuel production
Plasma-Catalytic Conversion	Uses plasma to activate CO_2 molecules at low temps, combined with	SDG 7: affordable and clean energy	- Enables CO_2 conversion at lower temps and pressures

	catalysts to yield CH_4, CH_3OH, syngas	SDG 9: industry, innovation and infrastructure	- Suitable for intermittent renewable electricity integration
Bioconversion (Microbial/Algal)	Converts CO_2 into biofuels using algae, cyanobacteria, or acetogenic bacteria	SDG 2: zero hunger SDG 6: clean water and sanitation SDG 12: responsible consumption & production SDG 13: climate action	- Produces bioethanol, biogas, biodiesel from CO_2 - Some pathways use wastewater or non-arable land - Promotes circular bioeconomy

Addressing the twin challenges of climate change and fossil fuel dependence requires innovative strategies that transform carbon dioxide from a waste product into a valuable resource. These technologies form a closed-loop system where CO_2 emissions are not only reduced but repurposed, supporting the principles of a circular carbon economy. This integrated framework aligns energy production with environmental responsibility by creating sustainable fuel alternatives while minimizing carbon footprints, thus paving the way toward a more resilient and resource-efficient future. Table 5 discusses the integrated attributes towards sustainability.

Table 5: integrated attributes towards achieving sustainability

Integrated function	Relevant SDGs	Mapping justification
Carbon mitigation	SDG 13: climate action	Helps decrease atmospheric CO_2 through capture, storage, and transformation.
Green fuel production	SDG 7: clean and affordable energy	Produces low-emission fuels for transportation, power, and heating applications.
Sustainable industry	SDG 9: industry, innovation and infrastructure	Encourages cleaner technologies and innovation across manufacturing and energy sectors.
Circular economy	SDG 12: responsible consumption and production	Repurposes CO_2 emissions into valuable outputs, promoting resource efficiency.
Rural and urban resilience	SDG 11: sustainable cities and communities	Enables local CO_2 conversion systems for distributed and community-level benefits.
Water and land optimization	SDG 6: clean water and sanitation SDG 15: life on land	Algal systems utilize wastewater and avoid conflict with agricultural land use.
Food security	SDG 2: zero hunger	Provides alternative protein and feed sources via CO_2-fed microbial or algal biomass.

4. Conclusion

The escalating urgency to address climate change and shift toward sustainable energy solutions has propelled CO_2 conversion technologies into a leading role in the green innovation landscape. A comprehensive and sustainable strategy that unites carbon capture, storage, and utilization (CCSU) with various catalytic approaches such as thermocatalysis, electrocatalysis, photocatalysis, and plasma-assisted catalysis alongside biological conversion techniques, offers a robust framework for producing renewable fuels from CO_2. This integrated methodology not only boosts conversion performance and product specificity but also draws on renewable energy, contributing to circular economy goals by transforming greenhouse gas emissions into usable resources. Such an approach aligns closely with international climate commitments and underpins several key SDGs. Additionally, the use of decentralized and flexible systems fosters environmental resilience in both rural and urban areas, supports resource-efficient farming practices, and enhances food security supporting a more inclusive and sustainable global development agenda.

The application of artificial intelligence and machine learning is anticipated to significantly influence the future of CO_2 conversion technologies. As these digital tools evolve, they will enhance the precision and speed of process optimization, improving both conversion efficiency and product selectivity. Despite their potential, these technologies remain in the developmental stage and will require substantial investment in research to reduce costs and maximize effectiveness. Their success is closely linked to the availability of renewable energy sources like wind and solar, making the expansion of clean energy infrastructure essential.

For large-scale implementation, these systems must be both economically viable and scalable, necessitating improvements in material efficiency and reductions in production costs. Governmental support through incentives, subsidies, and regulation can accelerate their adoption. Equally important is raising public awareness and acceptance to increase demand and drive market uptake. Infrastructure development such as facilities for CO_2 capture, transport, storage, and fuel synthesis are critical for broad deployment. Collaborative efforts between academia, industry, and policy-makers will be key to fostering innovation, sharing knowledge, reducing costs, and accelerating technology development. To conclude, tapping into the combined strengths of emerging CO_2 conversion technologies within a circular economic model offers a transformative path to reducing carbon emissions, expanding the green fuel portfolio, and advancing sustainability worldwide. Realizing the full potential of this vision will require continued investment in research, supportive policy frameworks, and multi-stakeholder collaboration at scale.

Declarations

Data Availability Statement
This is not applicable.

Competing interests
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.

Highlights
Environmentally conscious growth: capturing carbon in circular economy for resilient futures.
Integrated strategy: tangible solutions for policy-makers and industries.
SDG roadmap: simultaneous progress in economic, environmental, and social dimensions.
Promoting circularity: converting CO_2 to fuels promotes sustainable way towards circularity.

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