Advances in the catalytic conversion of CO_2

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Abstract. The catalytic conversion of carbon dioxide (CO_2) offers significant potential for reducing greenhouse gas emissions and producing valuable chemicals, driven by advancements in sustainable technology and environmental regulations. Current catalytic methods for CO_2 conversion primarily include photocatalytic, thermocatalytic, and electrocatalytic processes, each using distinct energy sources—light, heat, and electricity. Among these, photocatalytic conversion stands out for its environmental friendliness, as it utilizes solar energy to reduce CO_2 into useful products. However, challenges such as low photon absorption efficiency and catalyst degradation have limited its large-scale application. Recent research has focused on enhancing photocatalyst performance by introducing nanomaterials and multifunctional catalysts. Innovations, such as noble metal-doped semiconductors and two-dimensional materials like graphene, have shown promise in improving light absorption, electron transfer, and stability. This paper reviews the latest advancements, explores the advantages and limitations of each method, and suggests optimization directions for effective CO_2 catalytic conversion, with an emphasis on achieving industrial viability.

1 Introduction

With the rapid development of industrialization and urbanization, the burning of fossil fuels has caused a large amount of CO_2 emissions and caused a series of ecological and environmental problems, such as the intensification of the greenhouse effect, ocean acidification, and sea level rise [1]. To alleviate the harm caused by CO_2, A lot of research has been conducted. For example, CO_2 could be directly captured and stored, but this method cannot fundamentally solve the problem. Another promising approach is to convert CO_2 into other high-value chemicals through chemical reactions, such as methanol, olefin, even glucose, and starch, which can not only realize the efficient use of CO_2, but also truly realize the recycling of carbon resources [2]. Therefore, chemical utilization plays a pivotal role in the management of CO_2. With the intensification of global climate change and rising CO_2 emissions, efforts to mitigate these impacts have become increasingly urgent. Converting CO_2 into valuable chemicals not only addresses carbon emissions but also enables the efficient recycling of carbon resources. While several methods have been developed, challenges such as high energy consumption, low efficiency, and product selectivity remain significant obstacles. So, this article will talk about catalytic conversation methods for

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CO_2.So that, it would make the knowledge of these more detailed. This paper reviews the primary catalytic methods for CO_2 conversion, discussing their mechanisms, advantages, and limitations, as well as the potential for future improvements in this critical area.

2 Catalytic conversion methods for CO_2

The catalytic conversion of carbon dioxide (CO_2) presents significant research opportunities, driven by advances in science and technology and by increasing environmental regulations aimed at mitigating greenhouse gas emissions. Moreover, growing awareness of sustainable and green chemistry has further encouraged the exploration of CO_2 conversion as a method for creating high-value chemicals and fuels from CO_2, contributing to carbon resource recycling and a circular economy. Currently, CO_2 catalytic conversion methods are primarily categorized into photocatalytic, thermocatalytic, and electrocatalytic conversion, each employing different energy sources—light, heat, and electricity, respectively. Each method has its own set of advantages and limitations that impact its efficiency, scalability, and industrial feasibility.

Photocatalytic technology, for instance, is considered environmentally friendly due to its ability to use sunlight as an energy source, making it a promising method for sustainable CO_2 reduction. However, practical application remains limited by several challenges. Photocatalysts typically have low photon absorption efficiency, with many only utilizing the ultraviolet (UV) spectrum, which constitutes less than 5% of sunlight. This narrow absorption range greatly restricts overall conversion efficiency. To address this, researchers have developed semiconductor catalysts doped with noble metals, such as platinum and gold, which have shown enhanced photon absorption and electron transfer capabilities. For example, platinum-doped titanium dioxide (TiO_2) has demonstrated significantly improved CO_2 conversion efficiency, as the noble metals expand the catalyst's light absorption to include the visible spectrum. Such doped catalysts also facilitate better charge separation, thereby reducing electron-hole recombination rates and enhancing reaction efficiency.

In addition, multifunctional catalysts, designed to simultaneously act as light absorbers and active sites for CO_2 reduction, have proven effective in increasing conversion rates. Recent studies indicate that these catalysts, often structured with multiple active components, can achieve improved CO_2 reduction efficiency by accelerating reaction kinetics and stabilizing reaction intermediates. The integration of two-dimensional materials, such as graphene and molybdenum disulfide (MoS_2), has further boosted photocatalytic activity. These materials provide a large surface area and unique electronic properties, which allow for more active reaction sites and enhanced electron mobility. The layered structure of these materials also contributes to their durability, making them suitable for long-term application in CO_2 reduction.

CO_2 electrochemical reduction technology is expected to become an important means of CO_2 conversion and utilization, the use of renewable energy to drive CO_2 electrochemical conversion, to achieve an effective artificial photosynthesis process, open new renewable energy storage and CO_2 resource conversion and utilization of sustainable development model. Researchers are developing new catalysts, such as nanostructured metals, ion-modified metals, and organic and inorganic hybrid materials, to improve the efficiency of the electrochemical CO_2 reduction process. Hsieh et al. prepared a coral-like nanostructured Ag electrocatalyst and found that a stable chemical bond was formed on the surface of Cl^- and Ag nanocoral [3]. Compared with polycrystalline Ag, the electrochemical surface area of this material increased by 20 times, showing relatively high catalytic activity.

2.1 Photocatalytic conversion

Photocatalytic technology is a highly efficient and environment-friendly purification technology that uses semiconductors as catalysts and light as activation energy. Research on photocatalytic solar energy conversion and utilization is of great significance for optimizing our country's energy structure and achieving the goals of "emission peak" in 2030 and "carbon neutrality" in 2060. Photocatalytic reduction of CO_2 involves absorbing light energy with photocatalysts, which then convert this energy into chemicals like CO, CH_4, and CH_3OH. Catalysts are crucial in this process, serving both as adsorbents for CO_2 and as agents for light energy conversion. However, finding efficient catalysts remains a challenge, and scaling up these processes for large-scale applications is still difficult. Similarly, photocatalytic conversion of nitric oxide is also a hot topic, such as photocatalytic oxidation, photocatalytic reduction, and photocatalytic direct decomposition.

2.2 Thermocatalytic conversion

Thermocatalytic conversion is a significant method for utilizing CO2. It involves providing thermal energy to drive chemical reactions that transform CO2. Key processes include CO2 hydrogenation, catalytic reforming, and transesterification. Among these, CO_2 hydrogenation is notable for producing various chemical raw materials, such as carbon monoxide, methane, methanol, and olefins, thereby offering efficient CO_2 utilization [4].Thermocatalytic conversion typically requires high temperatures and pressures, which pose challenges for catalyst durability. Common thermocatalytic reactions include the Fischer-Tropsch process, which converts CO_2 into liquid fuels and chemicals, and CO_2 reaction with epoxides to produce cyclic carbonates, an eco-friendly chemical. The choice of catalyst greatly impacts reaction pathways and product selectivity. Recently, dual-metal catalysts and composite catalysts based on porous materials have shown potential for enhancing both efficiency and selectivity in thermocatalysis, thereby reducing energy consumption while achieving higher yields.

2.3 Electrocatalytic conversion

Among all strategies for the conversion of CO_2, electro reduction represents a green way for the fixation of CO_2 via the use of clean and renewable electricity. As one of carbonaceous products from CO_2 electro reduction, methane exhibits the highest combustion heat per unit mass (a calorific value of about 56 KJ/g), which serves as a promising energy carrier to generate heat and electricity, as well as gas power for vehicles. In addition to combustion,CH4 could be adopted to prepare syngas via the steam reforming process. Accordingly, the synthesis of CH4 from CO2 electro-reduction opens up a perspective to reach a carbon-neutral economy. Electrocatalytic reduction of CO2 uses electricity to convert CO2 into carbon-based chemicals or liquid fuels3. This process is complex due to the multi-step electron-proton transfer required, leading to a range of products. The high thermodynamic stability and chemical inertness of CO2 necessitate significant energy input for its direct conversion5. Developing highly efficient electrocatalysts is crucial for scaling up these processes and producing valuable chemicals. The key to efficient CO_2 electrocatalysis lies in selecting optimal catalysts. Ideal electrocatalysts exhibit high conductivity, stability, and product selectivity. Currently, copper-based catalysts show high selectivity for CO_2 reduction; however, product diversity complicates the separation process. Studies indicate that modifying catalyst nanostructures or surfaces significantly enhances catalytic performance. Additionally, emerging catalysts like metal-organic frameworks

(MOFs) and single-atom catalysts are gaining attention for their excellent stability and efficiency, opening new possibilities for scalable, cost-effective CO_2 electrocatalysis.

2.4 Comparison of catalytic methods

Photocatalysis, thermocatalysis, and electrocatalysis are distinct catalytic methods that facilitate chemical reactions, each utilizing different energy sources: light, thermal, and electrical energy, respectively. Selecting the most suitable method for specific applications can enhance reaction efficiency while reducing energy consumption and environmental impact. Each catalytic method—photocatalysis, thermocatalysis, and electrocatalysis—has distinct advantages for specific applications. Photocatalysis is advantageous in low-energy, solar-driven applications but is limited by low efficiency and dependency on sunlight. Thermocatalysis is suitable for industrial CO_2 conversion, especially for synthesizing fuels and chemicals, as it achieves high reaction rates but at high energy costs. Electrocatalysis, when powered by renewable electricity, provides a clean and efficient pathway for CO_2 conversion, making it ideal for low-carbon applications. However, its scalability is restricted by current equipment costs and product selectivity challenges. In practice, selecting the most appropriate method requires careful consideration of process conditions, cost, and environmental benefits to maximize both economic and ecological impact. Catalytic processes offer a promising route to convert CO2 into green, high-value products, thus playing a strategic role in addressing environmental and energy challenges. While promising, photocatalytic CO_2 conversion still requires significant advancements to overcome its current limitations. Future research could focus on developing catalysts that not only absorb a broader range of light but also exhibit high stability under prolonged light exposure, addressing issues of catalyst degradation. Additionally, optimization of reaction conditions, such as controlling reaction environments to minimize energy losses and integrating co-catalysts to improve electron dynamics, may enable more efficient and scalable CO_2 photocatalytic conversion. In conclusion, although challenges remain, the combination of innovative materials, multifunctional catalyst design, and reaction engineering has substantially advanced the field, bringing photocatalytic CO_2 conversion closer to feasible industrial application.

3 Major challenges and limitations in CO_2 conversion methods

The catalytic conversion of CO_2 is a promising field, offering potential solutions for carbon emissions reduction and resource recycling. However, each method—photocatalytic, thermocatalytic, and electrocatalytic conversion—faces unique challenges that limit its efficiency, scalability, and economic viability in industrial applications. This section will discuss the primary limitations of each method and suggest potential strategies for improvement [5].CO_2 conversion methods, including photocatalytic, thermocatalytic, and electrocatalytic processes, offer promising solutions for reducing carbon emissions and recycling CO_2 into valuable products. These methods are central to efforts aimed at mitigating the impacts of climate change by transforming CO_2 into chemicals, fuels, and other resources. However, each approach faces significant challenges that hinder its efficiency, scalability, and economic viability. Overcoming these challenges is essential for achieving large-scale, sustainable CO_2 conversion processes that can contribute meaningfully to global efforts to reduce carbon emissions.

3.1 Low efficiency and catalyst stability issues

Photocatalytic conversion is an environmentally friendly approach that leverages solar energy to reduce CO_2, mimicking the natural photosynthesis process. Despite its potential, this method faces several major limitations. One of the primary challenges is low photon absorption efficiency. Most photocatalysts currently in use are optimized to absorb ultraviolet (UV) light, which constitutes less than 5% of the solar spectrum. As a result, the overall efficiency of photocatalytic CO_2 reduction is severely limited by the inability to capture a large portion of the sunlight. To address this, researchers are exploring catalysts that can absorb a broader range of the light spectrum, especially visible light. Some promising strategies include doping traditional semiconductor materials with transition metals or incorporating plasmonic nanostructures to enhance light absorption.

Another significant hurdle in photocatalytic processes is the fast recombination of electron-hole pairs. In photocatalysis, the separation of electrons and holes is essential for initiating chemical reactions. However, the rapid recombination of these charge carriers significantly reduces the reaction efficiency and, as a result, the CO_2 conversion rate. To mitigate this, the development of heterojunctions or multi-layered structures has been proposed. These structures can help create more efficient separation of charge carriers, which prolongs the lifetime of the electrons and holes involved in the reaction, thereby improving overall efficiency.

Catalyst stability is also a critical issue in photocatalytic CO_2 conversion. Photocatalysts are prone to deactivation due to photochemical corrosion, which limits their long-term performance. To improve catalyst stability, researchers are focusing on more robust materials like graphitic carbon nitride ($g\text{-}C_3N_4$) and titanium dioxide (TiO_2), which show greater resistance to degradation. Surface modifications and hybrid materials are also being explored as means to enhance catalyst durability, ensuring that they remain functional for longer periods in real-world applications [6].

Despite ongoing research into these areas, achieving high efficiency and stable performance in photocatalytic CO_2 conversion remains a significant challenge. Overcoming these limitations will require continued innovation in catalyst design, reaction engineering, and system integration to enable scalable and cost-effective applications.

3.2 High energy consumption and selectivity challenges

Thermocatalytic conversion of CO_2 has proven effective in producing valuable chemicals and fuels, such as methanol and synthetic hydrocarbons. However, it faces several challenges that hinder its commercial viability. One of the major concerns is the high energy demand of the process. Thermocatalytic conversion typically requires temperatures above 200°C and pressures exceeding 10 MPa. These extreme conditions lead to significant energy consumption, which makes thermocatalysis both economically and environmentally challenging, particularly when using fossil fuels as the energy source. Research efforts are focused on developing catalysts that remain active at lower temperatures, thereby reducing the energy burden. For example, metal-organic frameworks (MOFs) and nanostructured bimetallic catalysts have shown enhanced activity at reduced temperatures and are being actively explored as alternatives.

Another challenge in thermocatalytic CO_2 conversion is the issue of product selectivity. CO_2 hydrogenation can produce a wide range of products, including methanol, methane, carbon monoxide, and higher hydrocarbons, depending on the reaction conditions and the properties of the catalyst. Achieving high selectivity for a desired product is difficult due to the complexity of the reaction pathways. Recent advancements in catalyst design, such as the development of catalysts with controlled pore structures and tailored active sites, aim to improve selectivity. Additionally, advanced preparation techniques like atomic layer deposition and surface modification allow for more precise control over reaction pathways, which could enhance product selectivity.

Catalyst deactivation due to prolonged exposure to high temperatures and pressures is another major issue in thermocatalytic CO_2 conversion. High temperatures can cause sintering (the process where catalyst particles coalesce), while carbon deposits, known as coking, can accumulate on the catalyst surface. Both of these factors lead to a reduction in catalyst efficiency over time. To address this, researchers are focusing on developing catalysts with higher thermal stability and greater resistance to coking. Some promising solutions involve using metal oxide supports or incorporating alkaline elements to prevent carbon deposition and enhance the catalyst's longevity.

Addressing these challenges will require a multifaceted approach that combines advanced catalyst design, energy-efficient reaction conditions, and robust system engineering. Developing thermocatalytic conversion processes that are economically and environmentally feasible will be key to realizing its potential on an industrial scale.

3.3 Cost and product selectivity limitations

Electrocatalytic CO_2 reduction is a clean and efficient way to convert CO_2 into valuable chemicals and fuels, especially when powered by renewable electricity. Despite its promise, electrocatalysis faces notable challenges that limit its widespread adoption. A primary issue is the high cost of catalysts, which often rely on noble metals such as gold, silver, and platinum. These materials are costly and rare, making them unsuitable for large-scale applications. To make electrocatalytic CO_2 reduction more economically viable, researchers are seeking alternatives made from earth-abundant materials, such as copper, nickel, and iron. Metal-free catalysts, like nitrogen-doped carbon materials, are also being explored as potential substitutes. Additionally, single-atom catalysts, where individual metal atoms are dispersed on a support material, have shown promise in maximizing catalytic efficiency while minimizing the amount of precious metal used.

Low selectivity for the desired product is another major challenge in electrocatalytic CO_2 reduction. The process involves multi-step electron-proton transfer reactions that can yield a mixture of products, including carbon monoxide, methane, ethylene, and formic acid. Achieving selectivity for a specific product is challenging due to competing reaction pathways. Researchers are working to enhance selectivity by designing catalysts with tailored electronic structures and surface properties. Modifying the electronic environment of the catalyst through doping or alloying can help steer the reaction toward a single product. Additionally, improvements in reactor design, such as adjusting electrolyte composition or applying membrane separators, can help create more controlled reaction conditions, further improving selectivity.

Electrode stability and degradation also pose significant challenges for electrocatalysis. During the conversion process, electrodes can undergo corrosion, dissolution, or poisoning by reaction intermediates, which leads to a decline in performance over time. To address this, strategies such as protective coatings, alloying metals for enhanced durability, and the development of novel supports that maintain structural stability while providing high conductivity are being explored. The use of robust materials like titanium or graphene-based supports has shown promise in extending the lifetime of electrodes and improving the overall economic feasibility of the process.

4 Conclusion

With the continuous acceleration of China's industrialization process, environmental problems, especially air pollution, have seriously threatened people's normal lives. It is urgent to practice the concept of sustainable development and effectively control air pollution. Catalytic technology provides an effective approach to the treatment of atmospheric pollutants and has been widely applied. Carbon dioxide is not only the main component of greenhouse gases, but also an abundant and renewable carbon resource. This paper introduces three main CO_2 conversion catalytic methods, including photocatalysis, thermal catalysis and electrocatalysis. In particular, it is mentioned that photocatalytic conversion is environmentally friendly because of its use of solar energy, but it also faces the challenge of low photon absorption efficiency and catalyst degradation, which limits its large-scale application. This study highlights recent research on enhancing photocatalyst performance through the introduction of nanomaterials and multifunctional catalysts, such as precious metal-doped semiconductors and two-dimensional materials (such as graphene), which show potential for improving light absorption, electron transfer, and stability, discusses the advantages and limitations of each catalytic method, and suggests directions for optimization of efficient CO_2 catalytic conversion. Finally, the importance of achieving industrial feasibility is emphasized, and optimization directions are proposed to promote the practical application of CO_2 catalytic conversion technology.

Looking forward, research on CO_2 catalytic conversion must focus on developing highly efficient, low-cost processes for large-scale industrial applications. In photocatalysis, the development of high-efficiency catalysts and optimized photon absorption pathways will remain crucial. In thermocatalysis, lowering reaction temperatures and enhancing catalyst selectivity are essential to minimize energy consumption and improve product purity. For electrocatalysis, future research should focus on enhancing electrode durability and product selectivity to meet scalability requirements. Furthermore, combining different catalytic methods, such as hybrid photocatalytic-electrocatalytic systems, may leverage the strengths of each approach to achieve higher CO_2 conversion efficiencies, contributing significantly toward carbon neutrality.

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