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Electrochemical Reduction of Carbon Dioxide: Progress Towards Carbon Neutrality

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Abstract:

By transforming carbon dioxide (CO2), a key greenhouse gas, into chemicals and fuels with added value, the electrochemical reduction of carbon dioxide (CO2) promises a possible avenue towards reaching carbon neutrality. The purpose of this review is to investigate recent developments in the creation of effective catalysts, electrode materials, and reaction conditions that are responsible for driving the CO2 reduction reaction (CO2RR). One of the primary areas of concentration is the utilization of metal-based, metal-organic, and molecular catalysts, all of which have shown considerable advances in terms of selectivity and conversion efficiency. In addition, the paper emphasizes the significance of reactor design, electrolyte optimization, and scaling methodologies, all of which are aimed at enhancing the practicability of CO2 electrochemical reduction on an industrial scale. Despite the significant progress that has been made, there are still questions that need to be answered, such as catalyst stability, energy efficiency, and economic feasibility. It is essential to address these concerns in order to make it possible to implement CO2RR on a wide scale as part of global efforts to reduce the effects of climate change and move towards energy systems that adhere to sustainable principles. The purpose of this review is to offer insights into potential future directions for research and technological innovation in the field of carbon management, namely in the area of carbon reduction.

Keywords: Electrochemical reduction, Carbon dioxide (CO_2) reduction, Carbon neutrality

Introduction:

One of the primary factors that contribute to climate change is the rising levels of carbon dioxide (CO2) in the atmosphere, which is mostly caused by human activities such as the burning of fossil fuels and the destruction of forests. With the intensification of worldwide efforts to ameliorate the consequences of climate change and progress towards carbon neutrality, there has been a considerable increase in the amount of attention paid to the development of technologies that are capable of effectively capturing and converting carbon dioxide into products that are useful. Among these technologies, the electrochemical reduction of carbon dioxide (CO2) (CO2RR) has emerged as a viable technique to not only lower CO2 levels but also develop value-added chemicals and fuels, such as carbon monoxide (CO), methane, ethylene, and alcohols. All of these are examples of molecules that can be produced

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through this process. The electrochemical reduction of carbon dioxide (CO2) has a number of benefits, including the ability to function under ambient conditions and the possibility of employing renewable electricity as a driving force, which makes the process sustainable and favourable to the environment. Furthermore, it offers the possibility of closing the carbon loop by recycling carbon monoxide into high-value compounds. These compounds can be utilized as chemical feedstocks or energy carriers, so contributing to the transition to a carbon economy that is circular. However, despite these advantages, there are still a number of obstacles that need to be overcome before CO2RR can be widely adopted. These obstacles are mostly associated with catalyst design, energy efficiency, product selectivity, and scalability. It is essential to design electrocatalysts that are both effective and stable in order to improve the efficiency of reactions, increase the selectivity of products that are sought, and decrease overpotentials. Researchers have investigated a wide range of materials, including metal-based catalysts, molecular catalysts, and metal-organic frameworks (MOFs), to determine whether or not they have the capability to reduce carbon dioxide (CO2) with a high degree of efficiency and selectivity. the most current developments in the field of CO2 electrochemical reduction, with a particular emphasis on the breakthroughs made in catalyst design, reactor optimization, and electrolyte system design. Additionally, it discusses the obstacles that stand in the way of the commercial viability of CO2RR, as well as potential solutions and future research areas that aim to bridge the gap between invention on a laboratory size and its implementation on an industrial scale. The electrochemical reduction of carbon dioxide has the potential to play a significant role in the worldwide efforts to attain carbon neutrality and sustainable energy systems. This promise can be realized by harnessing technologies that have advanced in recent years.

Mechanisms of Electrochemical CO_2 Reduction

Depending on the catalyst, electrolyte, and reaction conditions, the electrochemical reduction of carbon dioxide (CO2) is a complicated process that involves various reaction paths and intermediates. This is because the process is dependent on the catalyst. The fundamental goal of carbon monoxide (CO) reduction is to transform CO into products that have a higher value, such as carbon monoxide (CO), methane (CH2), ethylene (C2H2), formic acid (HCOOH), and alcohols. These products have the potential to be utilized as fuels or chemical feedstocks, so contributing to the move towards energy systems that are more sustainable.

❖ Fundamentals of CO_2 Reduction Reaction (CO_2RR)

At the surface of an electrocatalyst, the CO2 reduction reaction takes place. This is the location where CO2 molecules adsorb, where they go through the process of electron transfer, and where they are eventually changed into assorted reduction products. “The following are the stages that are included in the whole process:

1. **CO_2 Adsorption:** For the reaction to take place, it is necessary for molecules of carbon dioxide to adsorb onto the surface of the catalyst, which acts as the active site.

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2. **Electron Transfer:** The adsorbed CO_2 molecules receive electrons from the electrode, reducing them to intermediates such as CO_2^-, COOH, or $HCOO^-$. The nature of the catalyst determines the subsequent reaction pathways and product distribution.
3. **Protonation:** Protons, often supplied by the electrolyte, interact with the intermediates to facilitate further reduction, leading to the formation of products like CO, CH_4, or formic acid.
4. **Product Desorption:** The final reduction products desorb from the catalyst surface, allowing the cycle to continue.

❖ Reaction Pathways and Product Formation

The electrochemical reduction of CO_2 can follow several distinct reaction pathways, depending on the electrocatalyst and reaction conditions. These pathways result in different products:

- **Formation of Carbon Monoxide (CO):** CO is one of the simplest products of CO_2 reduction. The reaction typically follows the pathway $CO_2 \rightarrow CO_2^- \rightarrow COOH \rightarrow CO$. Metals like gold (Au), silver (Ag), and zinc (Zn) are known to favor CO formation due to their high selectivity for the COOH intermediate.
- **Formation of Methane (CH_4):** The reduction of CO_2 to methane requires a series of protonation steps and electron transfers. The pathway is $CO_2 \rightarrow CO \rightarrow CH_4$, and copper (Cu) is one of the most effective catalysts for methane production, promoting multiple electron transfer steps.
- **Formation of Formic Acid (HCOOH):** The reduction of CO_2 to formic acid occurs via the $HCOO^-$ intermediate. Bismuth (Bi), tin (Sn), and lead (Pb) are commonly used catalysts for selective formic acid production.
- **Formation of Ethylene (C_2H_4):** Ethylene is produced via the dimerization of CO intermediates, following the pathway $CO_2 \rightarrow CO \rightarrow C_2H_4$. Copper (Cu) is again an effective catalyst, as it facilitates both CO formation and subsequent C-C bond formation.

❖ Challenges in Achieving Selective Product Formation

The selective formation of a desired product from CO_2 reduction is one of the major challenges in CO_2RR”. The rivalry that occurs between numerous reaction pathways frequently results in a mixture of products, which makes separation more difficult and decreases the overall efficiency of the process. The selectivity of the CO2RR is affected by a number of factors, including the following:

- **Catalyst Material:** One of the most important factors that determines the reaction route that is most preferred is the nature of the catalyst. As an illustration, copper (Cu) tends to encourage the synthesis of multi-carbon compounds such as ethylene, but gold (Au) and silver (Ag) tend to favor the formation of carbon monoxide.
- **Applied Potential:** Additionally, the selectivity of CO2RR is influenced by the electrochemical voltage that is supplied to the electrode. With lower potentials, products such as carbon monoxide or formic acid are more likely to be produced, whereas with higher potentials, methane or multi-carbon compounds may be produced.

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- **Electrolyte Composition:** Product distribution can be considerably impacted by the type of electrolyte as well as the pH of the electrolyte. In contrast to basic electrolytes, which encourage the reduction of carbon dioxide, acidic electrolytes have a tendency to support hydrogen evolution as a competitive process.
- **Mass Transport and Reaction Kinetics:** “Efficient mass transport of CO_2 to the catalyst surface and the kinetics of electron and proton transfer are crucial for achieving high selectivity. Reactor design and electrolyte optimization play an important role in controlling these factors.

❖ Key Intermediates in CO_2 Reduction

Several intermediates play a critical role in determining the reaction pathway and final product during CO_2RR:

- **CO_2^- Radical:** The initial reduction of CO_2 involves the formation of a CO_2^- radical, which can further react to produce various intermediates like COOH or $HCOO^-$. The stability of this radical influences the reaction outcome.
- **COOH and $HCOO^-$:** These intermediates are crucial in the formation of CO and formic acid, respectively. Catalysts that stabilize COOH tend to favor CO formation, while those that stabilize $HCOO^-$ favor formic acid.
- **C_2 Intermediates:** For the production of multi-carbon products like ethylene, C-C coupling of CO intermediates is essential. The ability of a catalyst to facilitate this dimerization step is critical for forming complex hydrocarbons”.

❖ Competing Reactions: Hydrogen Evolution Reaction (HER)

When it comes to electrochemical CO2 reduction, one of the most significant obstacles is the competition with the hydrogen evolution reaction (HER), which can take place concurrently in aqueous electrolytes. As part of the HER, protons are converted into hydrogen gas (H2), electrons are redirected away from the carbon monoxide reduction reaction (CORR), and the overall efficiency is decreased. In order to achieve greater selectivity, it is crucial to design catalysts and reaction conditions that decrease HER while simultaneously encouraging CO2 reduction.

For the purpose of constructing effective catalysts and optimizing reaction conditions, it is essential to have a solid grasp of the mechanisms that are involved in the electrochemical reduction of carbon dioxide. In order to overcome the problems that are connected with CO2RR and to achieve the aim of converting CO2 into valuable products with high efficiency and selectivity, it will be essential to make advancements in the design of catalysts, selective reaction paths, and reactor engineering.

Conclusion:

The electrochemical reduction of carbon dioxide (CO2) has a great deal of potential as a long-term solution to the problem of lowering the levels of CO2 in the atmosphere and making a contribution to the worldwide effort to achieve carbon neutrality. By converting carbon dioxide, a greenhouse gas that is destructive to the environment, into useful fuels and

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chemicals, this technology provides a one-of-a-kind potential to effectively close the carbon bottleneck. The efficiency, selectivity, and scalability of CO2 reduction processes have been greatly enhanced as a result of recent improvements in catalyst design, reactor optimization, and electrolyte engineering. A significant amount of progress has been achieved in the field of metal-based catalysts, metal-organic frameworks (MOFs), and hybrid systems. These technologies have shown promising results in boosting selective CO2 conversion into products such as carbon monoxide, formic acid, methane, and multi-carbon compounds. Nevertheless, there are still obstacles to overcome, notably with regard to enhancing the stability of the catalyst, reducing the amount of energy that is consumed, and tackling the competing hydrogen evolution process (HER). In order to build systems that are cost-effective, robust, and scalable, and that are capable of meeting the demands of the industrial sector while retaining high levels of efficiency and selectivity, additional research is required. In addition, in order to make the most of the environmental benefits that this technology offers, it will be necessary to combine electrochemical CO2 reduction systems with renewable energy sources. However, ongoing innovations in materials science, reaction engineering, and energy integration hold the promise of making CO2RR a key technology in achieving carbon neutrality and addressing the global challenge of climate change. This is despite the fact that the path to commercial-scale adoption of CO2 electrochemical reduction is a complex one. The continuation of efforts in this area will pave the way for more sustainable energy and chemical industries, which will provide a feasible option for mitigating the effects that carbon emissions have on the environment.

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