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Rice Husk Biochar Based Metal Catalysts for Reducing Carbon

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Abstract. This article focuses on environmentally friendly biomass rice husk. As a widely available and sustainable agricultural waste, rice husk has shown great potential in the preparation of high-performance carbon-based catalytic materials. A series of technological process adopted to use rice husk biochar as the carrier for loading metals. Regulating and controlling CO_2 products by using different metals. The rice husk biochar-based metal catalysts have demonstrated the adsorption and catalytic mechanisms in the reduction of CO_2. These catalysts can effectively promote the conversion of CO_2 into high-value chemicals and fuels, providing a green pathway for resource utilization. Rice husk biochar-based metal catalysts still have disadvantages in regulation accuracy and long-term stability. With the development of technology and artificial intelligence, the application scope of this catalyst will be broadened, and the catalyst process will be further optimized. It has application potential in industrial waste gas treatment, agricultural carbon sequestration, and soil fertility improvement. In the future, further research on structure design and performance modification will help overcome current limitations. Contribute to carbon neutrality in the whole world.

Keywords: Rice husk biochar, Composite metal catalyst, Environmental protection, Carbon neutrality

1. Introduction

In recent years, global warming has become increasingly obvious. Carbon neutrality has become a common mission for all countries. Since the Industrial Revolution, human daily activities have led to large amounts of CO_2 emissions. This has raised a series of abnormal natural disasters, including the greenhouse effect, glacier melting, and extreme weather events. In order to deal with the crisis and reduce CO_2 emissions at the same time. Converting atmospheric CO_2 into valuable resources has become an urgent global challenge.

CO_2 is the primary greenhouse gas in the atmosphere, also a widely available and low-cost carbon resource. Catalyst technology converts CO_2 into fuels and chemical raw materials such as carbon monoxide, methane, and methanol. Reduced reliance on fossil energy. It has significant dual value in terms of both the environment and the economy.

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In agricultural production and daily life, rice husks are incinerated and landfilled. Not only does rice husk waste silicon and carbon resources, but also releases carbon dioxide, dust, and harmful gases. Further exacerbated environmental pollution. Rice husk has a natural silicon-carbon composite structure, which silica can be used as a template for the preparation of porous supports. It is also has the potential to be transformed into high-value materials.

Rice husk biochar-based metal catalysts have achieved some results up to now. For example, iron-based catalysts supported on rice husk can be applied in the reduction of carbon dioxide, with hydrocarbon fuels as the primary products [1].

This study mainly focuses on how to process rice husk biochar into a qualified support for metal catalysts, as well as the different catalytic effects brought by loading various metals. It also investigates the reaction mechanism of CO_2 reduction over rice husk biochar-based metal catalysts. This work provides a feasible strategy for carbon dioxide reduction and contributes to the achievement of carbon neutrality.

2. Preparation and structure regulation of rice husk derived biochar supports

2.1. The natural composite structure and carrier advantages of rice husk

Organic in rice husk interwoven with amorphous SiO_2 forms a three-dimensional structure. The proportion of SiO_2 can reach 15% to 20%, and the content of organic carbon is approximately 35% to 45% [2]. This natural composite structure not just a simple physical combination, but forms stable interfacial interactions through Si-O-C chemical bonds and hydrogen bonds. Therefore SiO_2 nanoparticles in the carbon matrix. Not only retains the high electrical conductivity and porous characteristics of carbon materials but also inhibits the collapse of the carbon matrix during high-temperature treatment by virtue of the rigid structure of SiO_2 [3,4].

Compared with traditional catalysts like activated carbon, carbon nanotubes, and graphene, rice husk has obvious advantages. Although have high superficial area, its pore structure is rather single and costs amounts of resources in the preparation process. It is very unfriendly to environmental protection and the efficient utilization of resources. Although carbon nanotubes and graphene have excellent properties, their preparation processes are complex and the yield rate in practical applications is not high. Therefore, using rice husk as carbon-based catalysts is excellent both in terms of cost and the difficulty of practical application.

2.2. The preparation method of rice husk biochar

The preparation process of rice husk biochar mainly includes three main steps: raw material pretreatment, pyrolysis preparation, and activation modification. Among them, pyrolysis is the core process. By adjusting the pyrolysis temperature, pyrolysis time, heating rate of pyrolysis and other parameters, the specific surface area, pore structure and other properties of rice husk biochar can be regulated.

The first step is pretreatment. Dust and various other impurities usually adhere to the surface of rice husks, which will affect the pyrolysis results. Therefore, some pretreatment is required before pyrolysis. The first step is washing and drying. Rinse the rice husks with deionized water 2~3 times to remove surface soil particles and soluble salts, and then dry at 105~110°C to control the moisture content below 5% [5]. Excessive moisture will increase pyrolysis energy consumption and may lead to pore collapse; insufficient drying will affect volatile release and result in uneven structure. The second step is crushing and screening. The dried rice husks are crushed and sieved [3]. After

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crushing, the particle size decreases, the heat and mass transfer area increases, the organic carbon decomposes more uniformly, the pore distribution becomes more concentrated, and the activator can fully contact with the carbon matrix, thus improving the activation efficiency. The third step is degreasing treatment. The waxy layer on the surface of rice husks will hinder volatile release and activator penetration, which can be removed by Soxhlet extraction or high-temperature roasting [3]. After degreasing, the pyrolysis efficiency is improved, and the surface of biochar is cleaner, which is conducive to subsequent metal loading and CO_2 adsorption.

The second step is pyrolysis. Pyrolysis is the key step for converting rice husk into biochar. Studies have shown that the effect of pyrolysis temperature on the properties of rice husk biochar is staged [3,5]. The changes in rice husk at different temperatures are listed in the table. To make better use of the special pore structure, a moderate pyrolysis temperature is preferred.

The third step is activation. The specific surface area and pores of rice husk biochar after pyrolysis are too small, so activation is required through physical or chemical methods. The physical method usually uses oxidizing gas to etch the pores at high temperature, making the original pores larger and looser. This method is environmentally friendly and can be applied on a large scale in industrial production. The chemical activation method combines rice husk biochar with chemical reagents and adjusts the pore size and structure through chemical reactions. Since rice husk biochar is in full contact with chemical reagents, the activation efficiency is relatively high, but chemical reactions will inevitably produce waste. In actual production and application, the activation method should be selected according to the application scenario and cost.

3. Design and loading strategies of metal active sites

3.1. Screening and characteristics of active metal components

The prepared rice husk biochar has favorable sites for metal loading. The selected active metal will directly affect the catalytic activity, product selectivity and stability of the catalyst. Therefore, it is necessary to select the appropriate active metal according to the desired catalytic effect. Rice husk is usually loaded with a single metal or a bimetallic to form the catalyst together. The table introduces common single-metal catalysts, bimetallic catalysts and their main functions. Common rice husk single-metal catalysts include Cu-based catalysts, Fe-based catalysts, Ni-based catalyst and Co-based catalysts. Single-metal supported catalysts have the problems of low selectivity and poor stability. Therefore, the introduction of another metal can achieve the complementation of advantages and disadvantages, and even double the reaction rate.

3.2. Loading methods of metal components

The loading method of metal components will directly affect the dispersion, particle size and stability of metals on the rice husk biomass support. Therefore, the metal loading method should be selected according to different metal characteristics and the expected effect in actual production. Common loading methods include impregnation, precipitation, in-situ pyrolysis and the sol-gel method.

The impregnation method is to soak rice husk biochar in a metal salt solution, stir for 4~8 h, dry at 110°C, and then calcine at 300~500°C to load metals onto rice husk biochar. The main advantages of the impregnation method are a simple process, low cost and easy scale-up production. However, it is prone to insufficient metal dispersion, concentrated metal distribution and agglomeration during loading.

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The precipitation method is to add precipitants such as NaOH and Na_2CO_3 into the metal salt solution, adjust pH to 8~10 to form hydroxide or carbonate precipitates, mix with biochar and then calcine. The contact area between the added precipitant and the metal salt solution is large, and the reaction is sufficient, so the loaded metal is well dispersed and closely combined with the support. However, it is difficult to operate in practical application, requiring precise control of reaction pH and precipitation rate.

The in-situ pyrolysis method is to mix rice husk biochar and metal precursor in a certain ratio and conduct pyrolysis directly to form the catalyst in one step. This results in a strong interaction between metals and rice husk biochar, but modular production is difficult to realize.

The sol-gel method is to mix metal alkoxide with biochar dispersion to form a sol, then carry out gelation, drying and calcination to remove organic components. The prepared catalyst has good particle size and dispersion. However, it has the disadvantages of high cost and long preparation time in practical application.

4. Reaction mechanism of CO_2 reduction over rice husk biochar-based metal catalysts

The catalytic reduction mechanism of CO_2 over rice husk biochar-based metal catalysts is a coupling process in which the rice husk support and metal active components synergistically regulate the reaction pathway. The process starts with the adsorption and enrichment of CO_2 molecules, forms key intermediates through activation and conversion, then generates target products via directional transformation, and finally realizes product desorption and regeneration of catalyst active sites. The precise matching between structural characteristics of the support and catalytic performance of metals completes the reaction.

4.1. Adsorption and enrichment of CO_2

Rice husk biochar forms abundant pore structures after pyrolysis and activation, resulting in a high specific surface area. These pores provide sites for CO_2 adsorption. CO_2 is adsorbed on the pores through van der Waals forces, forming a local high CO_2 concentration under mild conditions and greatly improving the adsorption probability of CO_2.

4.2. Activation of CO_2

The adsorbed CO_2 needs to break the C=O bond for further conversion, which is the core difficulty of the reaction. The synergistic effect of rice husk biochar and metals reduces the activation difficulty. The metal active sites provide electrons transferred to the antibonding orbital of CO_2 molecules, weakening the C=O bond and transforming CO_2 from a stable linear structure into an activated state [4]. The silicon-carbon composite structure and surface heteroatoms of rice husk biochar regulate the electronic structure of metals through metal-support interaction, enhancing the activation ability toward CO_2 and reducing the activation energy barrier [4]. The activation modes vary slightly with different metals: Ni and Co tend to activate CO_2 into CO intermediates, Fe easily forms CO or HCOO, and Cu prefers to generate HCOO intermediates, which lays a foundation for the subsequent directional product formation [5-9].

4.3. Transformation of intermediates

The surface adsorbed intermediates formed after activation generate target products through different transformation pathways. The transformation direction is jointly regulated by the type of

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metal components, pore structure of the support and metal-support interaction. The mesoporous structure of rice husk biochar provides sufficient space for the migration and coupling of intermediates, effectively promoting the formation of multi-carbon products [5,6].

4.4. Product desorption and catalyst regeneration

After the target products are formed, they need to desorb from the active sites to provide conditions for the next reaction. The special structure of rice husk biochar plays an important role in this process. The hierarchical pore structure of rice husk biochar forms efficient mass transfer channels. Small-molecule products (CO, CH_4) can diffuse and desorb rapidly through micropores and mesopores, and multi-carbon products can also migrate smoothly in mesopores, effectively reducing the desorption resistance [3,5]. Mild reaction conditions reduce energy consumption and avoid excessive adsorption of product molecules. The SiO_2 phase on the surface of rice husk biochar can inhibit the formation and deposition of carbon precursors, reduce blockage of active sites and ensure long-term stable operation of the catalyst [10]. Characterization of the used catalyst shows that the pore structure and metal particle dispersion of rice husk biochar-based metal catalysts remain good after long-term operation, with a carbon deposition rate of only 2.3% [10], confirming the excellent structural stability and regeneration ability of the catalyst system.

5. Challenges and future prospects

5.1. Challenges

Due to the tiny catalytic structure, rice husk biochar-based metal catalysts lack sufficient ability to regulate catalytic performance and rely heavily on experience in catalyst preparation. Insufficient regulation accuracy of the special pore structure and surface functional groups of rice husk biochar leads to incomplete structures, reducing the adsorption and transport rate of CO_2. The loaded metals are characterized by dispersion and instability. Particle agglomeration easily occurs at high loading, while insufficient active sites appear at low loading. For bimetallic catalysts, different degrees of alloying and synergistic effects between metals reduce product selectivity [6,7].

The long-term stability of rice husk biochar-based metal catalysts still needs to be improved, and performance degradation easily occurs in complex environments, such as metal particle sintering and support structure damage. Complex environments usually contain other impurity gases, some of which combine with metal active sites and cause irreversible changes in metals, leading to decreased catalytic efficiency, especially aggravated during long-term use.

5.2. Future prospects

Rice husk biochar-based metal catalysts show broad development prospects due to their renewable raw materials, low cost and environmental friendliness. With the development of computer technology and the application of artificial intelligence, rice husk biochar-based metal catalysts will develop toward technological innovation, performance breakthroughs, more diversified application scenarios and more industrial applications.

For catalyst structure regulation, computer-aided design can be used to adjust the pore structure and surface functional groups of rice husk to achieve specific catalytic effects. Some studies have also proved that atomic deposition technology can be used to achieve single-atom dispersion of metal active sites, greatly improving the utilization efficiency of active sites [3,11]. In terms of performance optimization, the non-noble metal–rare earth element composite system (such as Ni-La,

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Fe-Ce) is promising in the future. The electronic modification and anti-sintering effect of rare earth elements can simultaneously improve the activity and stability of catalysts [10,12].

The application scenarios of rice husk biochar-based metal catalysts will shift from single CO_2 reduction to multi-field and applications. In addition to traditional products, the coupled conversion technology of CO_2 with biomass derivatives (such as glycerol, lignin) to synthesize high-value-added fuels such as C_2^+ alcohols and long-chain hydrocarbons has high research value and development prospects [12,13]. Rice husk biochar-based metal catalysts also have many applications in the environmental protection field, such as the synergistic absorption and treatment of industrial waste gas, and the absorption and degradation of dissolved CO_2 mixed with heavy metals. In agriculture, carbon sequestration can be achieved by reducing CO_2, further improving soil fertility.

6. Conclusion

Driven by the global goal of carbon neutrality, the resource utilization of CO_2 has become a key approach to alleviating the greenhouse effect and energy crisis. As an agricultural waste, rice husk has a natural silicon-carbon special structure, which provides sites for metal loading and CO_2 adsorption. This paper studies the preparation of rice husk biochar-based metal catalysts and their application in CO_2 reduction reaction. The preparation and structural regulation of supports, design and loading strategies of metal active sites, catalytic reaction mechanism, existing deficiencies and future prospects of the catalysts are described. Rice husk biochar-based metal catalysts currently face some problems. These include insufficient precise performance regulation, poor long-term stability, and a lack of industrial adaptability. However, these catalysts have broad prospects in technological innovation, application expansion, and industrialization. This is due to the advantages of renewable raw materials and low cost. This study provides theoretical support and technical reference for the high-value utilization of rice husk and the resource conversion of CO_2.

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