Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA29032

Recent Advancements of Nanomaterials in the Field of CO_2 Photocatalytic Reduction

Zhengxi Lu

School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan, China
u202410912@hust.edu.cn

Abstract. With the acceleration of the global industrialization process, the greenhouse effect caused by excessive emissions of CO2 has become a serious challenge. Photocatalytic reduction of CO2 technology not only reduces the content of CO2 in the atmosphere, but also generates carbon-containing products, which have economic benefits. Nanomaterials have been widely used in the field of photocatalysis due to their unique optical, thermal, electrical, and chemical properties. This review summarizes the research progress of nanomaterials in the field, briefly introduces the basic situation and preparation methods of nanomaterials, the reaction principle of photocatalytic reduction of CO2, and the factors that may affect the conversion efficiency. In addition, the review focuses on the application of several typical nanomaterials, describes the properties, advantages, and disadvantages of TiO2, g-C3N4, and MOFs in detail, and lists their existing modification scheme in the field. Then, aiming at the existing problems in the field, such as low product selectivity, large-scale production difficulties, the review puts forward feasible solutions and prospects the future research direction in the field.

Keywords: Nanomaterials, Carbon dioxide reduction, Photocatalysis, TiO2, Heterojunction

1. Introduction

With the improvement of global industrialization and population growth, the greenhouse effect increases continuously. How to deal with CO_2 beyond the natural range has become an urgent problem to be solved. To increase economic benefits and energy reserves, reducing CO_2 and converting it into carbon resources has become the main research direction. At present, the main conversion methods include thermal catalysis, biocatalysis, electrocatalysis, photocatalysis and etc [1]. Among them, the photocatalytic method simulates photosynthesis and uses sunlight as the driving energy to reduce CO_2 to other carbonaceous compounds under the action of the catalyst. It has the characteristics of mild reaction conditions and rich driving energy. Compared with other methods, the photocatalytic method has the advantages of being friendly to the environment and sustainable development [2].

In photocatalysis, the photocatalyst determines the conversion efficiency. The photocatalyst has a large absorption coefficient of sunlight. It can absorb light of different wavelengths and has stable material properties with fewer side reactions. Nanomaterials have a small size effect and low

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.KA29032

reflectivity to light, which can be used as efficient light conversion materials. The surface effect of nanomaterials makes their specific surface area larger, and it is easier to combine with reactants than traditional materials, so as to improve the reaction rate, which is suitable as a photocatalyst. Therefore, it is of great significance to study the application of nanomaterials in the field of photocatalytic reduction of CO_2 for the development of photocatalysts in the future. So far, nanomaterials have been widely used in the field of photocatalytic reduction of CO_2.

This review first introduces the nanomaterials, briefly describes the basic principle of photocatalytic reduction of CO2, analyzes the factors affecting the reaction rate, and then summarizes the application of several typical nanomaterials in the field. Finally, review prospects for the development direction, which aims to provide a reference for the research and optimization of photocatalysts in the future.

2. Nanomaterials

Nanomaterials refer to materials with a size of 1-100 nanometers in at least one dimension, which can be divided into zero-dimensional nanomaterials, one-dimensional nanomaterials, and two-dimensional nanomaterials according to the difference in dimension [3]. Zero-dimensional nanomaterials refer to nanomaterials whose dimensions are between 1-100 nanometers, such as fullerene C_{60}. One-dimensional nanomaterials refer to nanomaterials with a dimension between 1-100 nanometers, such as nanowires and carbon nanotubes. Two-dimensional nanomaterials refer to materials with a single layer or a few layers of atomic thickness, such as graphene.

The synthesis methods of nanomaterials can be divided into physical methods and chemical methods. Physical methods include crushing, laser evaporation, spray, etc. Chemical methods mainly include vapor deposition, hydrothermal strategy, and atomic layer deposition [4]. In the review, chemical vapor deposition (CVD) and the solvothermal method are selected for description. CVD refers to the conversion of two or more solid reactants into a gaseous state, so that the generated gaseous reactants react to form volatile substances, and then transfer to the deposition area to form solid sediments. This method is usually used to produce two-dimensional nanomaterials with very small thickness, and the advantage is that the preparation process is easy to control [4]. However, CVD requires specific volatile substances such as metal organic compounds as reaction raw materials, which requires corresponding production equipment, resulting in high production costs. In the solvothermal method, the reactants are fed into a reaction vessel, and the physical properties of the product are controlled by adjusting the properties of the reactants and reaction conditions under high temperature and high pressure conditions. This method produces nanomaterials with high purity and a simple preparation process, making it suitable for large-area preparation [5]. The disadvantage is that precise control of reaction conditions and factors is required, and certain experience or high-precision equipment is needed for large-scale preparation.

The special characteristics of nanomaterial structures, such as small size effects, quantum effects, and surface effects, optimize the optical, thermal, and other properties of materials, making nanomaterials superior to traditional materials and making them an ideal choice for photocatalysts.

3. Reaction principle of photocatalytic reduction of CO_2

There is an energy band structure inside the photocatalyst consisting of a conduction band, a valence band, and a band gap. When the catalyst absorbs light equal to or greater than the bandgap energy, it will excite electrons to transition to the conduction band and generate holes in the valence band. Afterwards, electrons and holes will migrate to the surface of the catalyst respectively, during which

DOI: 10.54254/2755-2721/2026.KA29032

the catalyst will capture CO_2 and reducing agents. Electrons and holes undergo oxidation-reduction reactions, respectively, producing products, and then the catalyst separates from the reaction products [6]. Therefore, the photocatalytic reduction of CO2 reaction process can be divided into three main steps. Firstly, the catalyst absorbs light and converts it into chemical energy, producing electrons and holes. Afterwards, electrons migrate from the interior of the catalyst to the surface of the catalyst. Ultimately, electrons react with CO_2, and CO_2 is reduced to carbon-containing products.

There are several factors that affect the photocatalytic conversion efficiency in the above reaction process. In the stage of light energy absorption, the intensity and wavelength of light absorbed by photocatalysts are related to the structure of the catalyst itself, and the energy of the absorbed light directly affects the rate and quantity of electron generation. In the stage of photogenerated carrier separation, electrons and holes may undergo recombination before migrating to the catalyst surface. After recombination, they will not participate in the reaction, resulting in a decrease in photon utilization efficiency, and the migration rate will also affect the catalytic efficiency. When charge carriers reach the surface of the catalyst, whether there are enough electron and hole binding sites on the surface can also affect the efficiency. If there are few sites on the surface, it may lead to the loss of charge carriers and a decrease in the activity of the catalyst. In this process, whether the catalyst can efficiently capture reactants is also a factor that affects the efficiency, and low efficiency can also lead to a decrease in the utilization rate of electrons. After a single reaction, the reaction product should be efficiently separated from the catalyst. If the separation rate is too slow, it will lead to a decrease in the binding rate of the reactants, thereby reducing the conversion efficiency. From this, it can be seen that improvements can be made to existing photocatalysts, and more efficient photocatalysts can be studied.

4. Application of typical nanomaterials

4.1. Titanium Dioxide (TiO2)

TiO_2 has been widely used due to its high catalytic activity, low cost, and stable properties. However, TiO_2 has a large bandgap and only absorbs ultraviolet light, resulting in only a small portion of natural light being utilized. Therefore, it is necessary to modify TiO_2 to improve its utilization efficiency of light energy.

4.1.1. Metal doping scheme

Metal doping refers to the process of doping metals into a catalyst to alter its internal structure and enhance its performance. If transition metals such as iron and cobalt are doped into TiO_2, their bandgap will be reduced, and the range of light capture will be expanded from only ultraviolet light to visible light, while exhibiting high selectivity for methane. If doped with precious metals such as silver and gold, it will not only increase the range of light capture but also improve the separation and migration rate of electrons and holes [7,8]. For example, Li et al. synthesized Cu/TiO_2 catalysts with different exposed surfaces. In the experiment of photocatalytic reduction of CO_2 to CH_4, the CH_4 yield and selectivity of TiO_2 were 4.7μmol·g^{-1}·$h^{-1}$and 52.6% [9]. In contrast, different types of Cu/TiO_2 catalysts have better photocatalytic CO_2 reduction activity, among which the Cu/TiO_2 photocatalyst mainly exposed on the (001) surface has the best catalytic effect, with a CH_4 yield of 40.36μmol·g^{-1}·h^{-1} and a selectivity of 94.1% [9]. This experiment shows that the exposed (001) crystal plane in Cu/TiO_2 photocatalyst is beneficial for CO_2 adsorption and activation, and Cu ion doping mainly enhances the separation and transfer efficiency of photogenerated charges.

DOI: 10.54254/2755-2721/2026.KA29032

The metal doping scheme can improve photon capture and electron separation, but excessive metal doping can lead to a decrease in the charge layer space of the catalyst. When the penetration of sunlight exceeds the depth of the charge layer, the recombination rate of electrons and holes will increase, which is not conducive to photocatalytic reactions.

4.1.2. Constructing a heterojunction scheme

A heterojunction refers to a composite material composed of two semiconductor materials, which typically have close contact surfaces and different energy levels. When light is excited to generate electrons and holes, the two substances are attracted to two semiconductors with different energy levels, and oxidation-reduction reactions occur on the surfaces of the two semiconductors [7,8]. TiO_2 belongs to semiconductors with a wide bandgap and low energy levels. If it is combined with another semiconductor material with a small bandgap and high energy level, it will facilitate the migration of electrons and holes, expand the light capture range of TiO_2, and thus improve its photocatalytic activity. For example, Cheng et al. increased the light utilization range of the catalyst to 400-800 nm by forming a heterojunction between TiO_2 and Cu_2O, and determined that the band gaps of TiO_2, Cu_2O, and Cu_2O/TiO_2 heterojunctions with Cu_2O compositions of 0.1, 0.2, and 0.5 were 3.20, 2.09, 3.03, 3.0, and 2.94 eV. This means that under visible light irradiation, heterojunctions have higher photocatalytic activity than TiO_2 [10]. The photoluminescence experiment showed that the heterojunction with a Cu_2O composition of 0.2 has the highest quenching efficiency and exhibits significant ability to promote electron-hole separation [10].

The spatial separation strategy of constructing heterojunctions greatly reduces the probability of electron-hole recombination, unleashing the strong trapping ability and oxidation-reduction potential of heterojunctions, and greatly improving photocatalytic reduction efficiency. However, with the disadvantages of multiple side reactions and high costs, how to continue improving the method of constructing heterojunctions is still a problem that needs to be considered [7].

4.2. Graphitic Carbon Nitride (g-C3N4)

$g\text{-}C_3N_4$ is an n-type non-metallic polymer semiconductor photocatalyst with stable performance, moderate bandgap width (2.87 eV), high light energy utilization efficiency, and excellent catalytic performance in water photolysis, CO2 reduction, and pollutant degradation. $g\text{-}C_3N_4$ has a distinct non-local conjugated structure, which enables effective charge separation and transfer. $g\text{-}C_3N_4$ can be synthesized in bulk using low-cost nitrogen-rich precursors such as cyanamide and urea through a heat shrink process, with advantages such as low cost, environmentally friendly synthesis process, and biocompatibility [11]. However, the CO_2 binding sites of $g\text{-}C_3N_4$ are few, and the specific surface area is small, which limits its effectiveness and prompts researchers to improve it.

The original form of $g\text{-}C_3N_4$ usually exhibits a sheet-like stacked structure, resulting in problems such as a small specific surface area and few binding sites. Through morphological engineering, $g\text{-}C_3N_4$ can be converted into a two-dimensional material with a graphene-like structure, thereby obtaining the inherent surface effects and other advantages of nanomaterials [12]. For example, changing $g\text{-}C_3N_4$ to a spiral structure can expand the light capture range and significantly suppress electron-hole recombination. By changing to a two-dimensional planar structure, $g\text{-}C_3N_4$ will gain more active sites, a larger specific surface area, and a shorter electron migration distance, resulting in stronger CO_2 adsorption capacity. However, when the morphology changes, the band structure of $g\text{-}C_3N_4$ also changes, which may suppress the photocatalytic performance of the catalyst to some

DOI: 10.54254/2755-2721/2026.KA29032

extent. Therefore, in order to achieve better performance, it is necessary to consider multiple factors and carry out reasonable shape control when conducting shape engineering [12].

g-C_3N_4 can also improve performance by constructing heterojunctions, which can not only adjust the bandgap but also significantly suppress the recombination of photo-generated carriers. In addition, by designing heterostructures between different semiconductors reasonably, the occurrence of side reactions can be reduced and the CO_2 light conversion efficiency can be improved. For example, Li et al. constructed a hollow spherical heterojunction using SnS_2 and g-C_3N_4. The results showed that the porous structure of the hollow spherical structure significantly improved the light energy utilization efficiency by causing multiple reflections and increased the binding sites for CO_2, meanwhile. The band gap of the heterojunction decreased to 2.65 eV. The support connection function of the hollow sphere greatly reduces the charge transfer resistance, which is manifested in the experiment as a calculated average lifetime of 3.36 ns for photo-generated carriers in the heterojunction, significantly higher than g-C_3N_4 (1.72 ns) and SnS_2 (2.07 ns) [13]. This means that the probability of carrier participation in photocatalytic reactions increases, indicating that heterojunctions can effectively suppress the recombination of electrons and holes. Gao et al. introduced Ti_3C_2-MXene into g-C_3N_4 and then constructed a p-n heterojunction with Cu_2O. The Cu_2O/MX-CN photocatalyst prepared by this method exhibits excellent visible light photocatalytic CO_2 reduction performance. Among them, the LSPR effect of Ti_3C_2-Mxene injects hot electrons into g-C_3N_4, significantly improving electron transfer efficiency and promoting rapid charge transfer to Cu_2O. The composite of Ti_3C_2-Mxene and Cu_2O significantly enhances the photocatalytic CO_2 reduction activity of g-C_3N_4, with a CO yield of 28.4μmol·g^{-1}·h^{-1} and a selectivity of 93%, which is about 16 times faster than the original g-C_3N_4 [14]. The above explanation shows that constructing a heterojunction method can effectively improve the photocatalytic bottleneck of g-C_3N_4, with significant improvements in the separation and transfer of photogenerated carriers, product selectivity, and yield.

4.3. Metal Organic Framework materials (MOFs)

MOFs, as a new type of material, have attracted a lot of attention in the field due to their photocatalytic activity. The structure of MOFs is flexible and can be changed according to different situations to adapt to different composite materials. Its porous structure is able to reduce the migration distance of electrons to the catalyst surface. As a multiphase catalyst, it is easy to separate and recover from the reaction system, avoiding environmental pollution [15].

There are two main strategies for improving the performance of MOFs. Firstly, MOFs can be roughly divided into single-metal MOFs and multi-metal MOFs. MOFs composed of multiple metals exhibit higher CO_2 capture and product conversion rates compared to single-metal MOFs. For example, Yang et al. utilized a bimetallic modification strategy to design and synthesize a series of Cu-BTB-Fe bimetallic MOFs based on known structures of Cu-BTB-MOF, and evaluated their photocatalytic activity and selectivity for CO_2 reduction to CH_4 [16]. Specifically, under simulated sunlight irradiation, the CH_4 yield and selectivity of Cu-BTB-2wt%Fe increased from the initial 4.26μmol·g^{-1}·h^{-1} and 32.80% to 32.20μmol·g^{-1}·h^{-1} and 69.24%, indicating an effective improvement in the photocatalytic performance of the original catalyst [16]. Secondly, by combining MOFs with metal particles of different sizes, MOFs can efficiently separate products and promote reactions. Metal particles provide electron binding sites, thereby inhibiting electron hole recombination and providing active sites for oxidation-reduction reaction [17]. For example, by combining Cu metal nanoparticles with MOFs, the lower energy level of Cu facilitates the migration of electrons from MOFs to the conduction band, effectively reducing the recombination of photo-generated carriers.

DOI: 10.54254/2755-2721/2026.KA29032

Compared with the original MOFs, the CO yield of the improved catalyst increased by 2.7 times [18]. The above cases demonstrate that MOFs not only have excellent performance in the field but also have multi-directional improvement potential.

5. Challenges and improvements

Although nanomaterials have been widely used in the field, there are still challenges. For example, there is less research on product separation, and there is still research space in product selectivity, large-scale production, etc. This review briefly lists several improvement schemes here. In terms of product selectivity, by doping Cu into ZnS, the addition of Cu increases the electron density at the Fermi level, improves the reaction activity at the Cu site, and enhances the combination of the catalyst surface and CO intermediates, thereby improving the selectivity of CO. In addition, by anchoring single Au atoms to ultra-thin ZIS nanosheets, the introduction of Au atoms improves the efficiency of carrier separation and transfer, and Au atoms significantly enhance the activation of CO_2, reduce the energy barrier of *CO protonation, stabilize $*CH_3$ intermediate, and promote the selective generation of CH_4 by CO_2 photoreduction [19]. In terms of large-scale preparation, Huang et al. synthesized two isomorphic two-dimensional metal organic framework materials M-SA (M=Ni or Co) using low-cost succinic acid and showed excellent photocatalytic activity and selectivity [20]. And the large-scale energy-saving synthesis of Ni-SA can be realized by simple stirring at room temperature, which has great application potential, and provides a new way for the preparation and development of efficient two-dimensional MOF-based catalysts.

6. Conclusion

Nanomaterials have been widely used in the field of photocatalysis due to their unique properties. Due to the limited role of a single nanomaterial, compared with the single use, the combination of nanomaterials and other materials through various ways, such as metal doping, heterojunction construction, can play its photocatalytic value better. In the future, the research bottleneck in the current field can be studied from the following aspects. Researchers can design nanomaterials that efficiently separate reaction products to increase reaction rates. In addition, researchers can comprehensively consider various factors that affect efficiency to prepare catalysts, such as composite materials that combine a wide spectral response, a high carrier separation rate, and high product selectivity. Furthermore, researchers can use band engineering and reaction pathway regulation to improve catalysts by accurately matching bands and modifying surface active sites to suppress side reactions and enhance product selectivity. In the future, it is expected to develop a new type of catalyst with higher efficiency and lower cost, put it into production as soon as possible, provide a solution for the treatment of excess CO_2, and take a step closer to a carbon-neutral society.

References

[1] Dang, Y., Huang, R., Feng, X., Liu, G., Zhu, Y., & Zhang, Y. (2024). Application of Carbon Dots and Its Composites in the Field of Photocatalytic CO2 Reduction. Progress in Chemistry, 36(4), 575-585.
[2] Qin, D., Zhou, Y., Wang, W., Zhang, C., Zeng, G., Huang, D., ... & He, D. (2020). Recent advances in two-dimensional nanomaterials for photocatalytic reduction of CO2: insights into performance, theories and perspective. Journal of materials chemistry A, 8(37), 19156-19195.
[3] Li, Z., Wang, L., Li, Y., Feng, Y., & Feng, W. (2019). Carbon-based functional nanomaterials: Preparation, properties and applications. Composites Science and Technology, 179, 10-40.
[4] Guo, Y. T., & Yi, S. S. (2023). Recent advances in the preparation and application of two-dimensional nanomaterials. Materials, 16(17), 5798.

DOI: 10.54254/2755-2721/2026.KA29032

[5] Liang, P., Xia, Z., Feng, Y., Yang, W., Peng, H., & Zhao, S. (2024). Preparation methods of different nanomaterials and prospects for their application. New Chemical Materials, 52(8), 1-7.
[6] Karamian, E., & Sharifnia, S. (2016). On the general mechanism of photocatalytic reduction of CO2. Journal of CO2 Utilization, 16, 194-203.
[7] Chen, J., Li, T., An, X., & Fu, D. (2024). Photocatalytic reduction of CO2 by TiO2 Modified materials: recent advances and outlook. Energy & Fuels, 38(9), 7614-7636.
[8] Mutiara, S., Saputera, W. H., Devianto, H., & Sasongko, D. (2023). Recent Advances on the Utilization of TiO2-Based Catalysts in the Photocatalytic Reduction of CO2 to Methane. ChemistrySelect, 8(39), e202302536.
[9] Li, D., Li, Q., Zhou, Y., Zhang, Q., Ye, Q., Yang, R., & Jiang, D. (2024). Sha** and do** metal–organic framework-derived TiO2 to steer the selectivity of photocatalytic CO2 reduction toward CH4. Inorganic Chemistry, 63(33), 15398-15408.
[10] Cheng, S. P., Wei, L. W., & Wang, H. P. (2021). Photocatalytic reduction of CO2 to methanol by Cu2O/TiO2 heterojunctions. Sustainability, 14(1), 374.
[11] Khan, M. A., Mutahir, S., Shaheen, I., Qunhui, Y., Bououdina, M., & Humayun, M. (2025). Recent advances over the doped g-C3N4 in photocatalysis: A review. Coordination Chemistry Reviews, 522, 216227.
[12] Tang, J., Guo, C., Wang, T., Cheng, X., Huo, L., Zhang, X., ... & Xu, Y. (2024). A review of g-C3N4-based photocatalytic materials for photocatalytic CO2 reduction. Carbon Neutralization, 3(4), 557-583.
[13] Li, Y., Yin, Q., Zeng, Y., & Liu, Z. (2022). Hollow spherical biomass derived-carbon dotted with SnS2/g-C3N4 Z-scheme heterojunction for efficient CO2 photoreduction into CO. Chemical Engineering Journal, 438, 135652.
[14] Gao, Y., Wang, Y., Sun, R., Luo, Y., Xin, L., & Wang, D. (2024). Interfacial hot electron injection in Cu2O/MXene-g-C3N4 p-n heterojunction for efficient photocatalytic CO2 reduction. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 684, 133236.
[15] Chang, X. L., Yan, T., & Pan, W. G. (2024). Toward Tailoring Metal–Organic Frameworks for Photocatalytic Reduction of CO2 to Fuels. Crystal Growth & Design, 24(6), 2619-2644.
[16] Yang, H., Liu, G., Zheng, L., Zhang, M., Guan, Z., Liu, T., & Yang, J. (2024). Cu-Fe bimetallic MOFs with long lifetime separated-state charge for enhancing selectivity for CO2 photoreduction to CH4. Applied Catalysis B: Environment and Energy, 359, 124491.
[17] Purvika, A., Yadav, S., Jijoe, S. P., Tenzin, T., Divya, V., Shahmoradi, B., ... & Shivaraju, H. P. (2024). Improved metal-organic frameworks (MOFs) and their application in catalytic CO2 reduction: A review. Materials Today Sustainability, 26, 100745.
[18] Zhou, S., Li, H., Gao, H., Li, A., Li, T., Cheng, S., ... & Qu, W. (2025). Recent advances in metal-loaded MOFs photocatalysts: From single atom, cluster to nanoparticle. Chinese Chemical Letters, 36(1), 110142.
[19] Gao, W., Li, H., Hu, J., Yang, Y., Xiong, Y., Ye, J., ... & Zhou, Y. (2024). Recent advances of metal active sites in photocatalytic CO2 reduction. Chemical Science.
[20] Huang, N. Y., Chen, Z. Y., Hu, F. L., Shang, C. Y., Wang, W., Huang, J. R., ... & Xu, Q. (2023). Large-scale synthesis of low-cost 2D metal-organic frameworks for highly selective photocatalytic CO2 reduction. Nano Research, 16(5), 7756-7760.