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Is the Transformation of CO2 to Hydrocarbons via Non-Methanol-Mediated CO2 Hydrogenation Over a Cobalt Catalyst an Effective Method of Carbon Conversion?

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Abstract

This research examines how carbon IV oxide hydrogenation can counter climate change by removing CO2 from the atmosphere while generating valuable products such as hydrocarbons, oxygenates, and other chemicals. Limited to non-methanol-mediated hydrogenation through cobalt-based catalysts, this paper scrutinizes the effectiveness of CO2 conversion, the range of products produced, and other consequences when scaling up this process. Catalysts are vital in defining the efficacy of the process of CO2 hydrogenation with cobalt-based catalysts exhibiting high selectivity on long-chain hydrocarbons suitable for fuel purposes. The paper also discusses the Fischer-Tropsch Synthesis and the Reverse Water-Gas Shift reaction for CO2 conversion to hydrocarbons. However, some drawbacks are still associated with enhancing reaction conditions to reach higher efficiency of the process, for example, reducing the yield of undesired side products like methane. The review also considers one of the most critical barriers to widespread hydrogen use, namely, how to generate hydrogen efficiently and, most importantly, cleanly, and calls for solar and wind energy to create carbon-neutral hydrogenation. In addition, future improvements to the catalyst, particularly bimetallic and single-atom catalysts, are discussed as ways to increase the rate of conversion and the overall stability of the catalyst. As novel reactor designs, membrane reactors, and microreactor systems are introduced as opportunities for increasing reactor efficiency and selectivity. The review ends by pointing to the economic and sustainability issues of scale-up of the CO2 hydrogenation technologies, paying particular attention to the further research activities needed in the field of catalyst lifetime, process efficiency, and interaction with other CO2 capture systems for making this approach to be a valuable addition to the overall global carbon management strategy. This work also highlights the role of CO2 hydrogenation as a two-fold solution to climate change and as a solution to the current energy crisis due to the production of various valuable fuels and chemicals. The research results show that CO_2 *hydrogenation with a cobalt catalyst is a promising carbon conversion method, but its effectiveness depends on the development of more efficient catalysts and integration with sustainable hydrogen sources.*

Keywords: CO2 Hydrogenation, Fischer Tropsche Synthesis, Reverse Water Gas Shift Reaction, Cobalt Catalysts, Long-chain Hydrocarbons, Carbon Cycle

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INTRODUCTION

Fossil fuels come from the remains of plants and animals that have decayed over millions of years. The main sources of fossil fuels include coal, crude oil, and natural gas, which are formed from ancient organisms and are found in abundance in the earth's crust. These fuels have high carbon and hydrogen content, making them a source of energy that can be processed for various purposes (Sabrina, 2024). Fossil fuels play a crucial role in meeting energy needs, not only because they are relatively affordable, but also because the infrastructure that supports their distribution allows the results to be obtained at a lower cost. The combustion of fossil fuels produces carbon dioxide which plays a role in trapping heat in the atmosphere, making it a major factor in global warming and climate change. Since the industrial revolution, the massive use of fossil fuels has increased the concentration of carbon dioxide (CO_2) in the atmosphere by around 48 percent. Carbon dioxide (CO_2) is the main greenhouse gas that contributes to global warming. Since the Industrial Revolution, CO_2 levels in the atmosphere have increased significantly, reaching their highest levels in millions of years (Mukono, 2020). Although carbon dioxide has a lower heat absorption capacity than other greenhouse gases, its very large amount makes it the main cause of global temperature increase (Utami, 2022).

The burning of fossil fuels contributes to more CO2 concentration in the atmosphere, which causes climate change. The risk of climate change to health has been recognized as a global challenge that has the potential to threaten human life (Susilawati, 2021). Global warming is the process of increasing the average temperature of the atmosphere, oceans, and land of the Earth. Over the past century, the average temperature of the Earth's surface has increased by 0.74 ± 0.18 °C (1.33 ± 0.32 °F) (Environmental Agency, 2019). The increase in the earth's temperature not only causes an increase in temperature but also affects the climate system as a whole, which has an impact on various aspects of the environment and human life, including health.

As a result, there is a strong demand for the formulation of techniques that will reduce carbon emissions and create valuable downstream chemicals. In this regard, one of the most effective strategies is CO2 hydrogenation, which involves converting this gas into hydrocarbons, methanol, and other chemicals using hydrogen (Li et al., 2018). In addition, by utilizing this method, the amount of CO2 emissions can be minimized while providing the opportunity to produce valuable products that can complement various industries, such as fuel production and chemical processing (Atsonios et al., 2016).

Reducing CO2 emissions is a major challenge and requires long-term efforts. There are three main strategies that can be implemented to achieve this: reducing the amount of CO2 produced, storing CO2, and utilizing CO2. The first strategy focuses on improving energy efficiency and the transition from fossil fuels to lower carbon-intensive energy sources, such as hydrogen and renewable energy. CO2 storage, as the second strategy, involves the development of new technologies for capturing and sequestering CO2, which is now a fairly well-established process. In addition, the CO2 hydrogenation reaction has been proven to be one of the most significant CO2 chemical conversion methods, with great potential to support sustainable development in the energy and environmental sectors. This process not only reduces the amount of CO2 in the atmosphere but also produces valuable fuels and chemicals (Saedi et al., 2014).

Previous research by (Guo et al., 2018) showed that advanced bifunctional, cobalt, iron, oxide, and cobalt composite catalysts with high-value heavy hydrocarbons as target products are highlighted in this review. To date, a large number of hydrocarbon products have been produced from the above selective and highly efficient catalysts for CO2 hydrogenation, including low oleins (C2–C4), gasoline (C5–C11), linear a-oleins (C4–C17), aromatics (C6–C8), etc., which are desired in industry due to their excellent features as energy carriers. Despite the remarkable progress in the production of C2+ hydrocarbons from CO2, this process is still challenging and currently at the fundamental research stage. Most of the processes suffer from low single-pass conversion efficiency due to thermodynamic limitations, as well as too high selectivity of the by-product CO (20–70%).

Another study by (Torrente-Murciano et al., 2016) showed that the key role of the structure-property relationship of the iron/ceria catalyst support on the hydrocarbon selectivity and olefin-to-paraffin ratio for direct hydrogenation of carbon dioxide to hydrocarbons. The effects are directly related to the reducibility of different nanostructured ceria supports and their interactions with iron particles. Iron-based catalysts can be modified not only by the addition of promoters, which is commonly reported in the literature, but also by careful control of the ceria support morphology.

Catalysts play a very significant role in the catalytic hydrogenation of carbon dioxide because they determine the amount of conversion and the type of products developed. Transition metals such as cobalt, nickel, and iron are commonly used to convert low CO2 to hydrocarbons and methanol (Li et al., 2018; Liu et al., 2019). However, several issues need to be resolved to improve the efficiency, selectivity, and conditions of catalytic CO2 hydrogenation. In this review, we present an updated view of the recent developments in CO2 hydrogenation reactions with special emphasis on the selectivity and efficiency of the process, the versatility of the products that can be synthesized by this reaction, and the potential limitations of scaling up this process. Furthermore, potential areas for the future are discussed, which are based on the evaluation of the stability and reproducibility of the process.

RESEARCH METHODS

In this communication article, I described the methodology to compile state-of-the-art advances in the catalytic hydrogenation of CO2 to ethanol over cobalt catalysts. This research uses a literature review research method. Literature review is a research method used to collect and analyze the results of previous research. The results of the literature review are used as a theoretical basis and reference in research (Snyder, 2019). Google Scholar, ACS (American Chemical Society), and PubMed were my main literature databases since they offered the most complete coverage of the literature relevant to the task at hand. This search was designed utilizing a targeted search to identify relevant studies. A timeline of 2018–2023 was applied to ensure that the data was recent and relevant. Given that the product of focus is ethanol, I decided to limit my search to studies that did not relate to methanol in order to focus on a specific area of carbon conversion technology. The search terms used were "efficiency," "Cobal Catalyst/Catalysts," "CO2/Carbon Dioxide Hydrogenation," and "Carbon Conversion" to ensure that while the search captured studies focusing on the catalytic processes used, it also captured their efficiencies and specificities towards ethanol. The literature pool was heavily informed by my inclusion and exclusion criteria. Research articles, since they offer the most straightforward information on specific experimental approaches/results/interpretations relevant to CO2 hydrogenation over cobalt catalysts, were prioritized. To keep the review concentrated on original research findings, communication, review, and perspective articles were largely removed. Moreover, I excluded studies that were published prior to 2018 to provide a more up-to-date analysis of the research. I included only articles reporting C1 conversion to ethanol and those that targeted cobalt or cobalt compound catalysts. This particular strategy was key in reducing the numerous studies that, although generally focused on CO2 hydrogenation, were not narrowed to studying CO2 hydrogenation to ethanol through cobalt catalysis. I nevertheless came across considerable literature volume, including perspective and summary articles, which were abundant, because there is a strong interest and debate in the scientific community about the CO2 hydrogenation over different catalysts with a special focus on the cobalt catalysts for carbon to ethanol conversion. The data analysis technique used in this research uses the data analysis technique from Miles & Huberman which goes through three stages, namely data collection, data reduction and drawing conclusions.

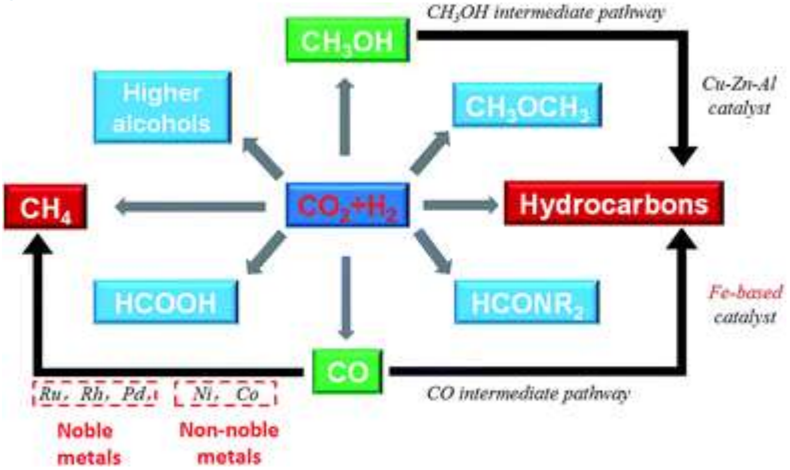

Fig 1. Pathways of CO2 Hydrogenation and Products Based on Catalytic Conditions

RESULT AND DISCUSSION

One significant benefit contributing to using CO2 hydrogenation for industrial applications is efficiency. Several factors influence conversion efficiency: temperature, pressure, and the type of catalysts involved in the process of CO2 conversion. For instance, cobalt-based catalysts with metal-organic frameworks have been used, and the results obtained indicate that when the temperature is set at 340°C and when the hydrogenation process involves two steps, the conversion of CO2 to other compounds was observed to be 37.5%. However, lower temperatures, within the range of 200 to 300°C, are usually characterized by a low conversion of CO2 (Ronda-Lloret et al., 2020). Notably, when FTS is performed at 260°C with a slightly lower conversion of CO2, up to 35% of the product is composed of longer-chain hydrocarbons containing five or more carbon atoms (C5+) that are desirable and commonly used (Hasan et al., 2021).

The chemical reaction for this process

$CO2+H2 \rightarrow CO+H2O$

Specifically, incorporating catalysts in these processes plays a vital role in boosting the general efficiency of CO2 hydrogenation. New technologies like single-atom catalysts and MOFs have been found to enhance both selectivity and carbon conversion. Also, the fine-tuning of reaction conditions, including temperature and pressure, has been reported to enhance the reaction's extent and increase product formation. However, new developments in reactor engineering, including microreactors and continuous flow systems, have also improved control of the reaction conditions, reducing energy use while increasing the efficiency of CO2 hydrogenation.

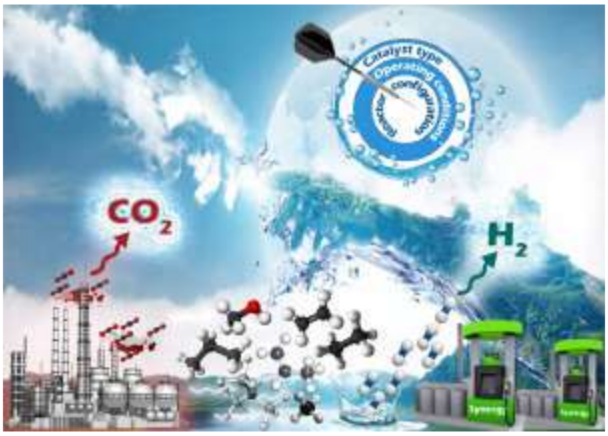

Fig 2. A diagram showing catalyst structure and reaction steps for CO2 hydrogenation

Products of CO2 Hydrogenation

The products formed through CO2 hydrogenation constitute alkanes, alkenes, alcohols, and aldehydes by the length of the carbon chain. The Fischer-Tropsch process, in particular, synthesizes liquid hydrocarbons suitable for fuel production, particularly in the C5-C11 range, which are ideal for gasoline and jet fuel applications (Gao et al., 2017). These longer hydrocarbon chains have higher energy density and are more valuable as fuel, particularly in mobile applications such as the transport sector. Nevertheless, light hydrocarbons, particularly methane and ethane, are still important mainly for stationary usage, including electricity and heat generation. These products, particularly by the Fischer-Tropsch process, are formed depending on the catalyst type and the reaction parameters (de Klerk & Maitlis, 2013). For example, cobalt catalysis produces longer hydrocarbons, while iron catalysis, which enhances the water-gas shift reaction, is more versatile in producing hydrocarbons of varying lengths.

The chemical reaction for this process

$(2n+1)H_2+nCO \rightarrow C_nH_{2n+2}+nH_2O$, where **n** represents the hydrocarbon chain length.

Besides hydrocarbons, CO2 hydrogenation can also produce oxygenates like methanol and ethanol (Wang et al., 2019). These products are worthwhile as they take center stage within chemistry and source the best fuels. Methanol can mainly be synthesized into other chemicals, such as formaldehyde and acetic acid, which are fundamental to chemical industries (Yang et al., 2017). Many works are focused on directly reducing CO2 to methanol over copper-based catalysts. Although the selectivity in methanol may be high, the general conversion rate is comparatively low and the catalyst loses its activity over prolonged usage. Furthermore, such improvements as bimetallic catalysts are still being considered to enhance selectivity for specific products that conform to the intended use.

The chemical reaction for this process

$CO_2+3H_2 \rightarrow CH_3OH+H_2O$

The versatility of using CO2 hydrogenation is that it can be a platform technology for producing both fuels and chemical feedstock and, therefore, is a core technology in the framework of a circular carbon economy. Nonetheless, further developments of the catalyst and the process are still needed to realize such predictions. Improving the selectivity of certain products without sacrificing efficiency would be crucial in further developing the technology for commercial applications.

Implementation & Sustainability

The introduction of CO2 hydrogenation at the industrial scale has certain limitations: sustainability and cost efficiency. Energy input for hydrogen production is a significant challenge, occupying a substantial share of energy. Currently, the most common method of generating hydrogen is steam methane reforming, which in turn releases CO2. To address this, the exploitation of renewable energy sources, namely solar or wind power, to generate hydrogen through water electrolysis is pursued. This coupling of renewable energy with CO2 hydrogenation could lead to an accurate carbon–neutral or even a carbon–negative process.

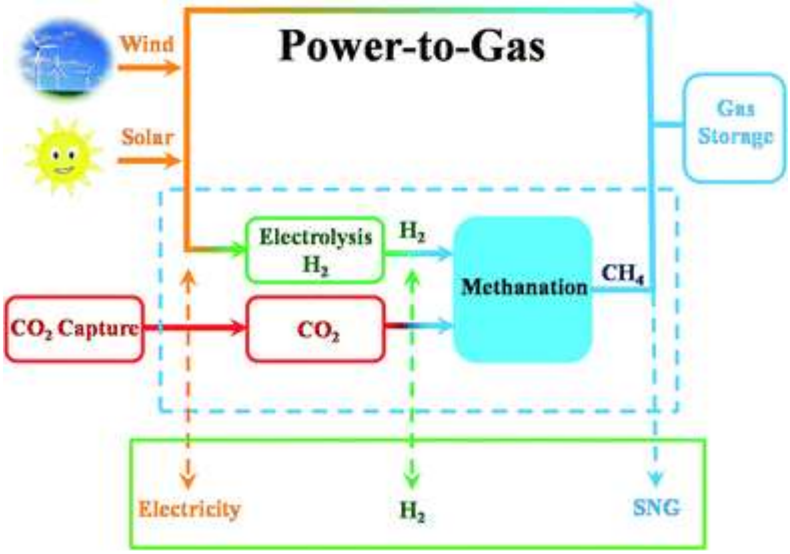

Fig 3. A diagrammatic representation of the flow of the proposed CO 2 to methanol conversion process.

Moreover, the cost of capturing carbon IV oxide and the hydrogenation process is equally expensive (Smit et al., 2014). The uptake of CO2 from industrial sources like power plants or cement factories is also an added cost. However, as the field matures, new technologies like Direct Air Capture (DAC) and carbon scrubbers, which are still under development, could bring down the cost (Xiang et al., 2019). The integration of CO2 capture with hydrogenation presents a route for cutting emissions and making money through the generation of valuable chemicals and fuels.

Another important point that should be discussed is the issue of catalyst stability. Promoters, especially those made of precious metals, deteriorate at some point and can only be replenished with new ones (Stöcker, 1999). Further studies are underway to develop more stable catalysts that maintain high activity over the long term to minimize catalyst deactivation and improve the service life of the catalytic system. In addition, the recyclability of the catalysts, particularly cobalt and iron ones, will be decisive for reducing the environmental impact of the hydrogenation of CO2 in the future.

Future Prospects

The future of the CO2 hydrogenation process holds significant potential as further work aims at attaining higher sustainability and efficiency. One of the most critical areas of development is the application of renewable power to generate electricity used to split water for hydrogenation. This shall improve the technology's total carbon-less capability, making it a much more environmentally friendly technique for producing hydrogen gas (Saeidi et al., 2021). The other vital element that has emerged is the perfecting of catalyst technology. Scientists are trying to develop a new generation of even more efficient, stable, and selective catalysts (Yan et al., 2022), and significant research is being carried out on bimetallic and single-atom catalysts. These developments should enhance the yield and selectivity of the targeted products, such as longer-chain hydrocarbons, and improve the catalyst lifetime to make the process more financially viable. Also, several emerging technologies in the reactor designs, such as the membrane and micro reactors, are expected to enhance process efficiency and scalability. While industries and governments apply CO2 capture technologies, CO2 hydrogenation serves both goals – as a capture method and the supply of valuable chemicals and fuels – as a critical component in building a sustainable, low-carbon world.

CONCLUSION

The research results show that CO_2 hydrogenation using a cobalt catalyst is a promising carbon conversion method, especially to reduce CO_2 concentrations in the atmosphere and provide an alternative energy source. This process offers great potential for recycling CO_2 into valuable hydrocarbons that can be integrated into today's industrial systems. However, the effectiveness of this method still depends on several main factors, such as the development of more efficient and effective catalysts, as well as integration with sustainable hydrogen sources. The main challenges in implementing this technology include the high energy requirements for hydrogen production and the costs required on an industrial scale. Therefore, further research efforts are needed to improve catalyst efficiency and optimize hydrogen production processes using renewable energy. So, with the world's increasing focus on carbon neutral and carbon negative solutions, CO_2 hydrogenation has the potential to become one of the key technologies in the transition to a more sustainable energy system. If existing challenges can be overcome, this technology will not only contribute to mitigating climate change but also become a source of innovative new fuels and chemicals.

REFERENCES

Atsonios, K., Panopoulos, K. D., & Kakaras, E. (2016). Investigation of technical and economic aspects for methanol production through CO2 hydrogenation. *International Journal of Hydrogen Energy*, *41*(4), 2202–2214.

de Klerk, A., & Maitlis, P. M. (2013). What Can We Do with Fischer–Tropsch Products? *Greener Fischer-Tropsch Processes for Fuels and Feedstocks*, 81–105.

Dinas Lingkungan Hidup. (2019). Pemanasan Global (Global Warming). https://dlh.bulelengkab.go.id/informasi/detail/artikel/pemanasan-global-global-warming-76. Accessed February 3, 2024.

Gao, P., Li, S., Bu, X., Dang, S., Liu, Z., Wang, H., Zhong, L., Qiu, M., Yang, C., & Cai, J. (2017). Direct conversion of CO2 into liquid fuels with high selectivity over a bifunctional catalyst. *Nature Chemistry*, *9*(10), 1019–1024.

Guo, L., Sun, J., Ge, Q., & Tsubaki, N. (2018). Recent advances in direct catalytic hydrogenation of carbon dioxide to valuable C 2+ hydrocarbons. *Journal of Materials Chemistry A*, *6*(46), 23244-23262.

Hasan, M. M. F., Rossi, L. M., Debecker, D. P., Leonard, K. C., Li, Z., Makhubela, B. C. E., Zhao, C., & Kleij, A. (2021). Can CO2 and renewable carbon be primary resources for sustainable fuels and chemicals? In *ACS Sustainable Chemistry & Engineering* (Vol. 9, Issue 37, pp. 12427–12430). ACS Publications.

Li, W., Wang, H., Jiang, X., Zhu, J., Liu, Z., Guo, X., & Song, C. (2018). A short review of recent advances in CO 2 hydrogenation to hydrocarbons over heterogeneous catalysts. *RSC Advances*, *8*(14), 7651–7669.

Liu, M., Yi, Y., Wang, L., Guo, H., & Bogaerts, A. (2019). Hydrogenation of carbon dioxide to value-added chemicals by heterogeneous catalysis and plasma catalysis. *Catalysts*, *9*(3), 275.

Mukono, H. J. (2020). *Analisis Kesehatan Lingkungan Akibat Pemanasan Global*. Airlangga

University Press.

Ronda-Lloret, M., Wang, Y., Oulego, P., Rothenberg, G., Tu, X., & Shiju, N. R. (2020). CO2 hydrogenation at atmospheric pressure and low temperature using plasma-enhanced catalysis over supported cobalt oxide catalysts. *ACS Sustainable Chemistry & Engineering*, *8*(47), 17397–17407.

Saeidi, S., Najari, S., Hessel, V., Wilson, K., Keil, F. J., Concepción, P., Suib, S. L., & Rodrigues, A. E. (2021). Recent advances in CO2 hydrogenation to value-added products—Current challenges and future directions. *Progress in Energy and Combustion Science*, *85*, 100905.

Sabrina, I. Z. *(2024)*. Bahan Bakar Fosil adalah: Pengertian, Manfaat, dan Dampak. https://solarindustri.com/blog/bahan-bakar-fosil/. Accessed February 3, 2025.

Saeidi, S., Amin, N. A. S., & Rahimpour, M. R. (2014). Hydrogenation of CO2 to value-added products—A review and potential future developments. *Journal of CO2 utilization*, *5*, 66-81.

Smit, B., Reimer, J. A., Oldenburg, C. M., & Bourg, I. C. (2014). *Introduction to carbon capture and sequestration* (Vol. 1). World Scientific.

Stöcker, M. (1999). Methanol-to-hydrocarbons: catalytic materials and their behavior. *Microporous and Mesoporous Materials*, *29*(1–2), 3–48.

Susilawati. (2021). Dampak perubahan iklim terhadap kesehatan. *Scientific Of Environmental Health and Diseases (e-SEHAD)*, *2*(1), 25-31.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of business research*, *104*, 333-339.

Torrente-Murciano, L., Chapman, R. S., Narvaez-Dinamarca, A., Mattia, D., & Jones, M. D. (2016). Effect of nanostructured ceria as support for the iron catalysed hydrogenation of CO 2 into hydrocarbons. *Physical Chemistry Chemical Physics*, *18*(23), 15496-15500.

Utami, S. N. (2022). Mengapa Penggunaan Bahan Bakar Fosil Menyebabkan Pemanasan Global?. https://www.kompas.com/skola/read/2022/05/17/101712769/mengapa-penggunaan-bahan-bakar-fosil-menyebabkan-pemanasan-global. Accessed February 3, 2025.

Wang, L., He, S., Wang, L., Lei, Y., Meng, X., & Xiao, F.-S. (2019). Cobalt–nickel catalysts for selective hydrogenation of carbon dioxide into ethanol. *ACS Catalysis*, *9*(12), 11335–11340.

Xiang, Y., Kovarik, L., & Kruse, N. (2019). Rate and selectivity hysteresis during the carbon monoxide hydrogenation over promoted Co/MnOx catalysts. *Nature Communications*, *10*(1), 3953.

Yan, C., Waitt, C., Akintola, I., Lee, G., Easa, J., Clarke, R., Geng, F., Poirier, D., Otor, H. O., & Rivera-Castro, G. (2022). Recent advances in plasma catalysis. In *Industrial & Engineering Chemistry Research* (Vol. 61, Issue 23, pp. 7675–7678). ACS Publications.

Yang, H., Zhang, C., Gao, P., Wang, H., Li, X., Zhong, L., Wei, W., & Sun, Y. (2017). A review of the catalytic hydrogenation of carbon dioxide into value-added hydrocarbons. *Catalysis Science & Technology*, *7*(20), 4580–4598.