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Article

Is ChatGPT a Reliable Source for Writing Review Articles in Catalysis Research? A Case Study on CO₂ Hydrogenation to Higher Alcohols

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Abstract: ChatGPT is an AI language model trained on vast amounts of text data, including scientific papers, providing a comprehensive understanding of catalysis. However, its reliability in catalysis research is unknown. To evaluate reliability, we compared a ChatGPT-generated review article on heterogeneous catalysts for higher alcohols synthesis by CO₂ hydrogenation to published peer-reviewed papers. Although the ChatGPT review article covers most necessary parts, it lacks sufficient discussion of the reaction mechanism. The core sections are too general, being not specific enough to the topic, and contain errors. The lack of citations further increases unreliability. While ChatGPT can provide much content on catalysis, it is insufficient and inaccurate for research on specific topics.

Keywords: ChatGPT; heterogeneous catalysis; CO₂ hydrogenation; reliability

1. Introduction

Artificial Intelligence (AI) is the simulation of human intelligence in machines that are designed to think and act like humans ¹. It encompasses the creation of computer programs and systems that can carry out tasks requiring human intelligence, such as speech recognition, visual perception, language translation, information analysis, pattern recognition, and decision-making ^{2,3}. AI plays a critical role in scientific research by offering new tools for data analysis ⁴, knowledge discovery ^{5,6}, and repetitive task automation ^{7,8}. As a result, it is widely used across a range of scientific disciplines, including information science, mathematics, medicine, materials science, geoscience, life science, physics, and chemistry ³.

In the field of chemistry research, the lack of comprehensive and analytical theories for the structures, properties, and transformations of macroscopic substances leads to a reliance on unreliable heuristics and fragmented rules. AI has the potential to revolutionize chemistry by recognizing patterns from vast data and transforming how complexity is managed ³. AI has been applied in several sub-fields of chemistry, including analytical and computational chemistry, organic chemistry, catalysis, and medical chemistry ³. AI has helped in overcoming the limitations of manual feature selection methods ^{9,10} and has improved the accuracy and efficiency of various computational

theories^{11,12}. Additionally, AI has empowered robotics to automate molecule synthesis^{13,14} and has assisted in exploring extensive catalyst design spaces^{15,16}. Furthermore, AI has facilitated chemical screening in toxicology with reduced ethical concerns¹⁷.

AI has also been widely utilized in the field of catalysis research, playing a significant role in improving the efficiency and accuracy of the research process. AI can be applied in several key ways, including predictive modeling of catalytic reaction kinetics and mechanisms^{18,19}, assisting in the screening of potential catalysts for a specific reaction^{20,21}, optimizing reaction conditions such as temperature, pressure, and concentration^{22,23}, and real-time monitoring and control of catalytic processes²⁴.

ChatGPT is a particular AI technology that utilizes the Generative Pretrained Transformer (GPT) architecture. It is trained on large amounts of text data to generate human-like responses in natural language processing tasks, making it ideal for conversational applications^{25,26}. In essence, ChatGPT is an AI model designed specifically for conversational purposes. ChatGPT is a powerful tool for scientific research, enabling researchers to quickly and efficiently summarize scientific papers and articles, analyze large amounts of data to uncover patterns and correlations, answer complex scientific questions in a variety of fields, and assist in the process of reviewing scientific literature²⁵. With its broad understanding of the scientific world, derived from its training on diverse text data, ChatGPT can significantly streamline and enhance the research process, providing researchers with a valuable resource in their pursuit of knowledge²⁷.

As an AI language model, ChatGPT has been trained on a vast amount of text data, including scientific papers and articles, allowing it to have a comprehensive understanding of the field of catalysis. In terms of catalysis, ChatGPT's training data may include information on various topics such as types of catalysts, including homogeneous, heterogeneous, and enzymatic catalysts and their specific applications. Additionally, it likely has information on catalyst design and synthesis, including the optimization of their properties for specific reactions. It may also have information on reaction kinetics, including the rate of chemical reactions involving catalysts and the factors that influence it. Furthermore, ChatGPT is likely to have knowledge of the thermodynamics of catalytic reactions, including activation energy and reaction enthalpies, as well as industrial applications of catalysts, such as their use in the production of chemicals, fuels, and materials. (*Generated by ChatGPT by asking what content on catalysis is involved in ChatGPT.*)

The application of ChatGPT in catalysis research is an area deserving of further investigation, as its reliability in this field is yet to be fully established. Despite being a valuable tool for scientific research and possessing a wealth of information on catalysis, the validity of its outputs in the context of catalysis research needs to be assessed. The utilization of CO₂ through catalytic conversion into value-added products is a crucial method for reducing CO₂ emissions and mitigating the effects of global warming. Higher alcohols, such as C₂₋₄OH, have a wide range of uses, including as fuels, fuel additives, solvents, reactants, and intermediates for chemical synthesis, making them highly valuable²⁸⁻³⁰. As such, the synthesis of higher alcohols through CO₂ hydrogenation has garnered significant attention³⁰⁻³³. In this paper, we evaluate the reliability of ChatGPT in catalysis research by analyzing a review paper generated by ChatGPT on heterogeneous catalysts for the synthesis of higher alcohols through CO₂ hydrogenation. We find that the generated review article lacks a sufficient discussion of the reaction mechanism. Additionally, the core sections are too general and not specific enough to the topic, containing errors and lacking citations. All these make the generated review article unreliable. While ChatGPT can provide a lot of content on catalysis, it may not be suitable for in-depth research on specific topics due to its inaccuracies and insufficiencies.

2. Methodology

A review paper on the topic of heterogeneous catalysts for the synthesis of higher alcohols through CO₂ hydrogenation was generated using ChatGPT (<https://chat.openai.com/>, ChatGPT Jan 9 Version). The authors first asked ChatGPT to provide an outline for the paper, then used the table of contents provided to request the generation of the content for each section. The resulting output from ChatGPT was then integrated and only underwent minor modifications by the authors to form a

complete review paper. The reliability of ChatGPT in catalysis research was evaluated by comparing the ChatGPT-generated paper to peer-reviewed research and review papers on the same topic.

3. Results and discussion

3.1. General comments on the ChatGPT-generated review article

The article was generated by ChatGPT after we asked it to create an outline and then requested the contents for each chapter based on that outline. The final result was a comprehensive review article on heterogeneous catalysts for higher alcohol synthesis via CO₂ hydrogenation, with minor modifications made to the generated contents. The chat history and generated review paper are available in the supporting information.

It is worth mentioning that the review paper generated by ChatGPT does not include figures or citations. As suggested by ChatGPT, it is a text-based AI model, not capable of providing figures or images as it can't generate or display them. It can only generate and provide text-based answers to questions. Besides, ChatGPT was not designed to provide references or citations for the information it provides. Its primary purpose is to generate human-like text based on the input it receives and the vast amounts of text data it was trained on. The information it generates is not always verifiable and should not be taken as authoritative or necessarily accurate. The absence of figures decreases the visual appeal and readability of the generated content, while the lack of references or citations undermines the credibility and reliability. Other challenges that may arise when using ChatGPT to generate a review article include the possibility of generating incorrect information, producing harmful or biased content, and having limited knowledge of events and developments after 2021 ²⁶.

3.2. Evaluation of the structure of the review article

Initially, we requested ChatGPT to produce an outline for a review article focused on heterogeneous catalysts for the synthesis of higher alcohols such as ethanol, propanol, and butanol through CO₂ hydrogenation. ChatGPT drafted an outline for a review article on the assigned topic, which includes five sections: introduction, CO₂ hydrogenation reaction, heterogeneous catalysts for CO₂ hydrogenation, case studies, and conclusion. Moreover, ChatGPT also suggested the contents should be included in every chapter of the review article (Table 1).

Table 1. An outline of the review article on the topic of heterogeneous catalysts for the synthesis of higher alcohols through CO₂ hydrogenation.

Chapter title	Contents of the chapter
1. Introduction	• Brief overview of the importance of higher alcohols as renewable energy sources and chemicals • Summary of current methods for their synthesis, including CO₂ hydrogenation • Statement of the research area and the motivation for the review
2. CO ₂ hydrogenation reaction	• Description of the CO₂ hydrogenation reaction and the products formed • Discussion of the challenges associated with the reaction, such as selectivity and stability
3. Heterogeneous catalysts for CO ₂ hydrogenation	• Overview of different types of heterogeneous catalysts used for CO₂ hydrogenation, such as metals and metal oxides • Comparison of the advantages and disadvantages of different catalysts • Discussion of the factors that affect catalyst performance, such as composition, crystal structure, and surface properties • Detailed description of specific catalysts and their performance in CO₂ hydrogenation
4. Case studies	• Comparison of the results obtained with different catalysts • Discussion of the factors that determine the catalyst performance in different conditions

5. Conclusion
- Summary of the main findings of the review
 - Discussion of the current challenges and opportunities in the field of CO₂ hydrogenation
 - Suggestions for future research directions.

As shown in Table 1, the introduction section provides a comprehensive overview of the background of the topic. It highlights the significance of higher alcohols as sustainable energy sources and chemicals, details the current state of their synthesis methods, and underscores the pressing need for a thorough review on this topic. Chapter 2, which focuses on the CO₂ hydrogenation reaction, offers a comprehensive understanding of the synthesis of higher alcohols through this method. It provides critical information, including reaction chemistry, key parameters, and challenges, which are essential for a deeper appreciation of the catalysis involved in the synthesis of higher alcohols through CO₂ hydrogenation. Chapter 3, which focuses on heterogeneous catalysts for CO₂ hydrogenation, serves as the cornerstone of the review article. It provides an overview and comparison of various heterogeneous catalyst types and highlights the key parameters that impact their performance, offering a comprehensive guide for designing effective catalysts. Chapter 4 delves into the examination of specific catalysts used in the CO₂ hydrogenation process to produce higher alcohols. It provides an in-depth analysis of the catalytic performances of these catalysts and the impact of reaction conditions on the outcome. The chapter presents a comprehensive overview of the most recent and advanced catalysts in the field. In the conclusion section, ChatGPT recommends summarizing the findings of the review, addressing the obstacles and prospects, and proposing future research directions.

Compared to other published review articles on the same topic ^{30,34}, the outline generated by ChatGPT appears to encompass most of the crucial aspects and has a well-structured presentation of information. However, the arrangement of the contents may vary, which is simply a matter of personal preference. Unfortunately, this review article does not cover the reaction mechanism, a crucial aspect of catalysis, as indicated by the outline. This is a significant shortfall of this review article.

3.3. Evaluation of the introduction section

The introduction chapter thoroughly covers the essential aspects of the background of higher alcohol synthesis. Despite its well-structured format, there are still some mistakes in the contents (Table 2). These mistakes occur when discussing the advantage of the high energy density of higher alcohols and the thermochemical conversion methods for higher alcohol synthesis. When discussing the chemical synthesis method for higher alcohol synthesis, several critical reactions are overlooked. Thus, the introduction section can be further improved.

Table 2. Comments on the contents of the introduction section.

Contents provided by ChatGPT	Comments by authors
They can be produced from sustainable resources, such as biomass, and they have a higher energy density than traditional biofuels like ethanol. They can also be blended with gasoline, diesel, or jet fuel, to increase their energy content and reduce emissions.	It is incorrect to state that higher alcohols have a higher energy density than ethanol, as ethanol itself is considered a higher alcohol. The energy density of higher alcohols is higher than that of methanol but lower than that of gasoline, diesel, or jet fuel, so blending cannot increase their energy density ³⁵ .
This process can be divided into two main categories: pyrolysis and gasification. Pyrolysis is	Gasification of biomass results primarily in the production of syngas, which can be further

the thermal decomposition of biomass in the absence of oxygen, while gasification is the partial oxidation of biomass in the presence of oxygen.	processed into higher alcohols through the application of heat, pressure, and catalysts. Direct gasification of biomass does not result in the production of higher alcohols ³⁶ .
Chemical synthesis.	When discussing chemical synthesis methods for the production of higher alcohols, several critical reactions CO hydrogenation ³⁷ , ethylene hydration ³⁸ , acetic acid hydrogenation ³⁹ , and hydroformylation ⁴⁰ reactions have been overlooked.

3.4. Evaluation of Chapter 2: Fundamentals and challenges of higher alcohols synthesis by CO₂ hydrogenation

In Chapter 2, ChatGPT addresses the basics and challenges of synthesizing higher alcohols through CO₂ hydrogenation. The chapter provides a brief overview of the reaction, an oversimplified mechanism, and the reaction conditions. The challenges related to catalyst selectivity, stability, low conversion rates, and cost are also discussed. However, in comparison to existing review articles, some crucial aspects regarding CO₂ hydrogenation to higher alcohols are not covered. The complex reaction system, including side reactions such as methane formation, methanol formation, and the reverse water gas shift reaction (RWGSR), is not introduced. Additionally, the provided reaction mechanism is oversimplified, omitting alternative routes for CO₂ hydrogenation to higher alcohols. The thermodynamics of the reactions, which plays a crucial role in determining the feasibility, direction, and extent of a reaction, is also not discussed. This information is vital for understanding catalytic phenomena and designing catalysts.

Additionally, there are some inaccuracies or mistakes in Chapter 2 (Table 3). For instance, the reaction equation lacks stoichiometric numbers and does not mention the presence of side products. The explanation of the reaction mechanism and the route is overly simplified. The impact of temperature and pressure, as well as the cause of low conversion rates, are not accurately described. This chapter could be improved by incorporating missing information and correcting these inaccuracies.

Table 3. Comments on the contents of Chapter 2.

Contents provided by ChatGPT	Comments by authors
$\text{CO}_2 + \text{H}_2 \rightarrow \text{R-OH}$	Stoichiometric number, which is helpful to determine the ratio of reactants in the feed is missing. The side product, water, which may influence the structure and performance of the catalyst, as well as the equilibrium conversion, is not presented. This equation, $n \text{ CO}_2 + 3n \text{ H}_2 \rightarrow \text{C}_n\text{H}_{2n+1}\text{OH} + (2n - 1) \text{ H}_2\text{O}$, encompasses all necessary information.
The CO_2 hydrogenation process can be divided into two stages: the activation of CO_2 and the reduction of CO_2 to the desired alcohol. In the first stage, the CO_2 is activated by the catalyst, which weakens the C-O bond and allows for the adsorption of CO_2 on the catalyst surface. In the second stage, hydrogen is added to the activated CO_2, which leads to the formation of the corresponding alcohol.	Adsorbed CO_2 can react with hydrogen to form the desired products, or it can be dissociated into CO and then react with hydrogenation ⁴¹.
Generally, methanol is the major product formed at low temperatures and pressures, while at higher temperatures and pressures, ethanol, propanol, and butanol are formed.	At low temperatures and low pressure, the formation of methanol is also difficult, methane is the main product under such conditions ⁴². The effects of temperatures and pressures on alcohol formation are complicated. The described trend is inaccurate.
Low conversion rate: CO_2 hydrogenation reaction is an endothermic process, which needs high energy input to activate the CO_2. As a result, the conversion rate of CO_2 to alcohols is relatively low.	The hydrogenation of higher alcohol synthesized by CO_2 hydrogenation is an exothermic reaction. The low conversion rate should be ascribed to the high kinetic barrier for higher alcohol formation.

3.5. Evaluation of Chapter 3: Heterogeneous catalysts for CO₂ hydrogenation to higher alcohols

In Chapter 3, an overview of heterogeneous catalysts for CO_2 hydrogenation to higher alcohols is provided. The categorization of these catalysts into metal and metal oxide catalysts by ChatGPT is insufficient, as many higher alcohol catalysts contain both metal and metal oxide. Supported catalysts, for instance, typically consist of a metal supported on a metal oxide, as exemplified by RhFeLi/TiO₂ ⁴³ and Pt/Co₃O₄ ⁴⁴. Furthermore, the synergy between metal and metal oxide sites is often vital for higher alcohol formation, as demonstrated by the importance of the synergy between metallic Co and Co oxide⁴⁵. Additionally, other catalysts, such as MoS₂ ⁴⁶, Mo₂C ⁴⁷, and Co₂C ⁴⁸, are also effective for CO_2 hydrogenation to higher alcohols but cannot be classified as metal or metal oxide-based catalysts. A more appropriate categorization approach would involve classifying

catalysts based on the types of constituent elements, as is commonly done in published review articles^{30,49}.

Then, ChatGPT examines metal catalysts, specifically palladium (Pd), platinum (Pt), and nickel (Ni) based catalysts, as well as bimetallic catalysts, for application in producing higher alcohols via CO₂ hydrogenation. While palladium has been demonstrated as an effective catalyst for ethanol production, only a limited number of examples have been published^{50–52}. Platinum, on the other hand, has been reported to be active for higher alcohol synthesis, but is typically combined with cobalt-based materials^{44,53,54}, and is regarded as a promoter for cobalt-based catalysts⁴⁴. However, even platinum-containing catalysts that produce small amounts of butanol exhibit low selectivity for this alcohol, with ethanol being the main product. Similarly, nickel is utilized as a promoter to enhance the synthesis of higher alcohols in cobalt-based catalysts, but results in only small amounts of propanol, lacking high selectivity⁵⁵. Thus, the assertion that platinum and nickel exhibit selectivity towards butanol and propanol, respectively, as suggested by ChatGPT, is deemed inadequate. Bimetallic catalysts, such as palladium-copper, have shown improved selectivity towards higher alcohols⁵². However, palladium-zinc and platinum-zinc suggested by ChatGPT as efficient are not known to be active catalysts for higher alcohol synthesis via CO₂ hydrogenation. Notably, while palladium, platinum, and nickel-containing catalysts have demonstrated activity in CO₂ hydrogenation to higher alcohols, they are not the most commonly studied catalysts^{30,34}, with rhodium, copper, cobalt, and molybdenum-based catalysts being more widely researched, which have not been discussed in the ChatGPT generated review paper.

In regards to metal oxide catalysts, ChatGPT suggested that TiO₂, ZnO, and CeO₂ exhibit activity. However, while metal oxides may be included as a component of certain CO₂ to higher alcohols catalysts for their ability to activate CO₂⁵⁶ and stabilize intermediates⁵⁷, act as a promoter^{58,59}, or serve as support⁶⁰, they typically require the presence of a metal to be active for higher alcohols synthesis. It should be noted that other oxides, such as SiO₂⁴⁸, Al₂O₃⁴⁵, MnO⁶¹, ZrO₂⁶², In₂O₃³³, and Ga₂O₃⁶³, play a similar role but are not included by ChatGPT.

Then, ChatGPT discussed the photocatalytic activity of TiO₂ for synthesizing ethanol from the reaction of CO₂ and water under light irradiation, which should not be confused with CO₂ hydrogenation reactions. Catalysts containing TiO₂ for CO₂ hydrogenation to higher alcohols, such as RhFe/TiO₂⁶⁴, Rh₁₀Se/TiO₂⁶⁰, NaCo/TiO₂⁴⁸, and PdCu/TiO₂⁵², are not covered in the ChatGPT generated review. ChatGPT suggests that ZnO can be used alone or as a support for metal to selectively produce propanol. While ZnO-containing catalysts such as K/Cu-Zn⁶⁵ and NaCo/ZnO⁴⁸ exist, there is no evidence of their selectivity for propanol or the application of sole ZnO catalysts for CO₂ hydrogenation to higher alcohols. Similarly, CeO₂ can be used as a promoter (e.g. RhCe/SiO₂⁵⁸) or support (e.g. Rh/CeO₂⁵⁹) for CO₂ hydrogenation to higher alcohols, but ChatGPT's assertion of their high selectivity for high butanol is not proven, and sole CeO₂ is not active for higher alcohols synthesis.

After that, ChatGPT presented a general comparison between the advantages and disadvantages of metal and metal oxide catalysts. However, as previously noted, it is not reasonable to categorize catalysts solely into these two groups. Therefore, a comparison between different catalysts for higher alcohol synthesis by CO₂ hydrogenation would require more information. The reliability of this chapter is compromised due to unreasonable categorization and lack of information on representative catalysts.

The factors that affect catalyst performance, including composition, crystal structure, and surface properties are also discussed in this chapter. First, the effects of composition on CO₂ hydrogenation to higher alcohols are discussed, with a focus on metal and metal oxide catalysts. As suggested by ChatGPT, copper, nickel, and cobalt-based metal catalysts possess high activity and selectivity for ethanol, propanol, and butanol, respectively. Similarly, copper oxide, nickel oxide, and cobalt oxide exhibit high activity and selectivity for ethanol, propanol, and butanol. However, it is worth noting that the discussion on composition effects lacks sufficient evidence from published articles and appears to be template-driven. Then, the effects of catalyst loading and catalyst support

choice are discussed, but the information provided is too general to be useful for understanding their specific effects in catalysts used for synthesizing higher alcohols through CO₂ hydrogenation.

In the following paragraphs, the effects of the crystal structure are discussed. Some examples (FCC vs HCP copper, FCC vs BCC cobalt, tetragonal vs cubic copper oxide, and tetragonal vs hexagonal nickel oxide) are provided after a general discussion on crystal structure's effects. However, these claims lack a reliable source to support them.

The effects of surface properties on the catalytic performance of metal and metal oxide catalysts are discussed, including examples of the impact of surface area. ChatGPT suggested that high surface area copper and copper oxide catalysts have been found to exhibit higher activity and selectivity for ethanol synthesis compared to their low surface area counterparts. Similarly, high surface area cobalt/nickel oxide catalysts have been found to have higher activity and selectivity for butanol/propanol synthesis. However, the provided examples lack reliable sources to support them and appear to be template-driven. Additionally, the effects of synthesis and post-treatment methods are discussed in general terms but not specific to higher alcohol synthesis by CO₂ hydrogenation.

Finally, the combined effects of various factors are discussed in this chapter. ChatGPT notes that copper catalysts' composition significantly influences their crystal structure and surface properties, ultimately impacting their catalytic activity and selectivity. Examples of promoter-enhanced copper catalysts, such as copper-zinc and copper-manganese, are presented. These catalysts' synergy leads to more active and selective surfaces and specific crystal structures, improving their overall performance. While the effects of zinc on CO₂ hydrogenation have been documented ⁶⁵, copper-manganese catalysts have only been reported in the literature for syngas conversion to higher alcohols ⁶⁶. Additionally, the discussion lacks sufficient catalytic data to substantiate its claims.

3.6. Evaluation of Chapter 4: Case studies

Chapter 4 provides case studies on heterogeneous catalysts for CO₂ hydrogenation to synthesize higher alcohols, which are categorized into copper, nickel, cobalt, and iron-based catalysts. This categorization differs from Chapter 3, which focused on metal (palladium, platinum, nickel, bimetallic catalysts) and metal oxide catalysts (TiO₂, ZnO, and CeO₂). Interestingly, copper and cobalt-based catalysts are commonly used for this purpose, while nickel and iron-based catalysts are less frequently reported. The chapter includes various examples of each type of catalyst.

Table 4 presents a list of catalysts discussed in Chapter 4. Copper, nickel, and cobalt catalysts with the same catalyst supports are provided, and their discussions are similar in format, lacking supports by catalytic results. For instance, in the case of Cu-ZnO catalysts, ChatGPT stated that they are active in the synthesis of ethanol and propanol through CO₂ hydrogenation. The addition of zinc oxide to copper enhances the catalyst's selectivity and stability. The descriptions of all the other catalysts follow a similar pattern, which reduces the reliability of the ChatGPT-generated review article. Among the catalysts listed in Table 4, only Cu-zeolite ⁶⁷ and Co-Al₂O₃ ⁴⁵ are reported active for higher alcohols synthesis by CO₂ hydrogenation. Other listed catalysts without further promotion are not effective.

Table 4. Catalysts discussed in Chapter 4.

Copper-based	Nickel-based	Cobalt-based	Iron-based
Cu-ZnO	Ni-ZnO	Co-MnO ₂	Fe-SiO ₂
Cu-MnO ₂	Ni-MnO ₂	Co-ZrO ₂	Fe-carbon
Cu-ZrO ₂	Ni-ZrO ₂	Co-Al ₂ O ₃	Fe-clay
Cu-Al ₂ O ₃	Ni-Al ₂ O ₃	Co-zeolite	Fe-zeolite
Cu-zeolite	Ni-zeolite	Co-graphene	Fe-metallic NP

ChatGPT conducted a performance comparison of various catalysts for the synthesis of higher alcohols through CO₂ hydrogenation. As stated by ChatGPT, the comparison can be complicated due to several factors that can influence catalyst performance, but certain trends can still be identified.

The discussion covers metal and metal oxide catalysts, the impact of support, and the effects of post-treatment.

When discussing general trends in metal catalysts, it is suggested that copper catalysts display the highest selectivity towards ethanol, while nickel catalysts show the highest selectivity towards propanol. Cobalt catalysts are active for synthesizing both ethanol and propanol but with lower selectivity compared to copper and nickel catalysts. While iron catalysts are active for synthesizing ethanol, propanol, and butanol, their selectivity is lower than that of copper, nickel, and cobalt catalysts. It should be noted that nickel and iron catalysts are not commonly studied and are typically used as promoters, rendering such comparisons meaningless.

Additionally, it is suggested by ChatGPT that metal oxide-based catalysts, including copper oxide, nickel oxide, and cobalt oxide, have demonstrated superior selectivity and stability in comparison to metal-based catalysts. However, the selectivity and stability of metal oxides can vary depending on the particular metal oxide used and the reaction conditions. It should be noted that, as far as the authors are aware, these metal oxides alone are not active for higher alcohol synthesis through CO₂ hydrogenation without metal promotion.

In regards to the effects of support, it is suggested by ChatGPT that catalysts supported on silica display the highest selectivity towards ethanol, while catalysts supported on zeolites show the highest selectivity towards butanol. However, it should be noted that most reported catalysts are typically selective towards ethanol. Moreover, the published paper provides evidence that the presence of zeolite does not have to result in the formation of butanol^{67,68}. Concerning the effects of post-treatment, ChatGPT suggested that catalysts that undergo calcination or reduction are more active for synthesizing higher alcohols through CO₂ hydrogenation. Nonetheless, since calcination and reduction are commonly used post-treatment methods, it is difficult to draw such a conclusion without additional information on the synthesis process.

In the following section, ChatGPT explores the factors that impact the performance of a catalyst in various conditions, including temperature, pressure, flow rate of reactants, and impurities. After a general overview, specific examples are given to demonstrate the effects of these factors. Since the influence of reaction conditions is very complicated, and the examples provided by ChatGPT often lack details about the catalysts, the described trend may be accurate in some cases but incorrect in others. To highlight the effect of temperature on CO₂ hydrogenation to form higher alcohols, two examples are provided. Copper-based catalysts exhibit higher activity but lower selectivity at high temperatures, while cobalt-based catalysts exhibit higher selectivity but lower activity at lower temperatures. However, it's important to note that these trends are not consistently observed in many published papers and in some cases, an increase in selectivity to higher alcohols is observed with a higher reaction temperature^{44,45,55,69}.

Regarding the effects of pressure on catalytic conversion of CO₂, ChatGPT suggested that for copper-based catalysts, increasing the pressure of CO₂ and H₂ can enhance the conversion of CO₂, but may decrease selectivity towards higher alcohols. For cobalt-based catalysts, decreasing the pressure of CO₂ may improve selectivity towards higher alcohols, but this may decrease the conversion of CO₂. However, there are some discrepancies in the literature, as An et al. observed decreased CO₂ conversion with unchanged ethanol selectivity when using copper-based catalysts at higher reaction pressures⁷⁰. Furthermore, the trends over cobalt-based catalysts have not been found in published papers.

When discussing the effects of the flow rate of reactants, it is suggested that a high flow rate of CO₂ favors high CO₂ conversion and low selectivity to higher alcohols over copper and cobalt-based catalysts. However, the effects of CO₂ flow rate or the GHSV (gas hourly space velocity) can be complex and depend on the specific catalyst used and the range of GHSV⁷¹. Therefore, the description provided may not be entirely accurate. The effects of impurities are also discussed, covering the impact of impurities such as water, sulfur, and chlorine, along with specific strategies to mitigate their effects. A general discussion on the subject is provided before delving into practical solutions.

3.7. Evaluation of the conclusion section

In the conclusion section, ChatGPT briefly summarizes the topics discussed and highlights the challenges and opportunities in the field of CO₂ hydrogenation to higher alcohols. Future research directions in the field include the development of more efficient and selective catalysts, optimization of reaction conditions, study of reaction mechanism, scale-up of the process, exploration of alternative feedstocks, exploration of other catalytic systems, and study of the reaction intermediates. However, more specific and detailed information may be needed to fully address the challenges and realize the potential of higher alcohols as renewable energy sources and chemicals.

4. Conclusions

ChatGPT is an artificial intelligence language model that has been trained on large amounts of text data, including scientific papers. As a result, it has a comprehensive understanding of catalysis. We requested ChatGPT to generate a review article on the topic of heterogeneous catalysts for higher alcohol synthesis by CO₂ hydrogenation. The article covers the necessary parts, including the introduction, CO₂ hydrogenation reaction, heterogeneous catalysts for CO₂ hydrogenation, case studies, and conclusion. However, the reaction mechanism is missing, which is an essential part of this topic. Although the introduction and CO₂ hydrogenation parts contain some errors, they can still provide the necessary background and fundamental knowledge on this topic. The heterogeneous catalysts for CO₂ hydrogenation and case studies are the core parts of this review article. However, their structure is not well-organized, and important content on this topic is missing. Many contents are also incorrect or unreliable. The conclusion section summarizes the topics discussed and highlights the challenges and opportunities, as well as future research directions in the field of CO₂ hydrogenation to higher alcohols, which are helpful but lacking more specific and detailed information. In conclusion, while ChatGPT can provide a considerable amount of content on catalysis, it is insufficient and inaccurate for research on specific topics.

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