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Peer Review File

Biochar-based catalytic upgrading of plastic waste into liquid fuels towards sustainability

Corresponding Author: Professor Yong Sik Ok

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Version 0:

Decision Letter:

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Dear Professor Ok,

Your manuscript titled "Biochar-based catalytic upgrading of plastic waste into liquid fuels towards sustainability" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Somaparna Ghosh, PhD
Associate Editor,
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #3 (Remarks to the Author):

This manuscript presents a valuable overview of biochar-based catalytic technologies for plastic waste valorization. However, a major revision is recommended prior to acceptance. Specifically, a more in-depth comparison with existing commercial catalytic methods is necessary, particularly regarding scalability and efficiency. Emphasizing the potential improvements and advancements offered by biochar-based catalysts would strengthen the manuscript's contribution to the field.

The abstract and introduction effectively establish the manuscript's foundation. However, the specific research gaps addressed by this review require clearer definition. Explicitly articulating the limitations of current technologies and demonstrating how biochar-based catalysts can overcome them would enhance the reader's understanding of the study's significance.
1. While the review comprehensively covers biochar activation and modification methods, including machine learning-guided optimization, the inclusion of experimental data or case studies would enhance its practical value. For instance, presenting examples of successful large-scale or pilot project implementations would be beneficial.
2. The environmental benefits of biochar-based catalysts are well-articulated. However, a more thorough exploration of the biochar production process's lifecycle assessment (LCA), including its carbon footprint and sustainability implications, is warranted. Furthermore, a discussion on the commercial scalability of these processes would be advantageous.
3. The conclusion would be strengthened by providing more specific future research directions. Identifying key areas for further study, such as enhancing catalyst stability or developing more efficient machine learning models, would offer readers a clearer roadmap for advancing this technology.

Reviewer #4 (Remarks to the Author):

This paper presents the biochar application, particularly with the respect to the use of biochar-based catalytic upgrading of plastic waste into liquid fuels. The overall content of this paper is of high quality and comprehensive. The title is informative and relevant. Judging from the introduction presented, the authors are well-understood about the research topic. The research trends obtained are practically meaningful and well-discussed from multiple angles and placed into context without being over interpreted. The conclusion was drawn based on evidence. Therefore, I have no reservation to recommend an acceptance for this well-written paper with only one comment as follow:
What are the limitations of biochar-based catalysts for catalytic pyrolysis and advanced oxidation technologies in the future works?

This manuscript presents a valuable overview of biochar-based catalytic technologies for plastic waste valorization. However, a major revision is recommended prior to acceptance. Specifically, a more in-depth comparison with existing commercial catalytic methods is necessary, particularly regarding scalability and efficiency. Emphasizing the potential improvements and advancements offered by biochar-based catalysts would strengthen the manuscript's contribution to the field.

The abstract and introduction effectively establish the manuscript's foundation. However, the specific research gaps addressed by this review require clearer definition. Explicitly articulating the limitations of current technologies and demonstrating how biochar-based catalysts can overcome them would enhance the reader's understanding of the study's significance.

1. While the review comprehensively covers biochar activation and modification methods, including machine learning-guided optimization, the inclusion of experimental data or case studies would enhance its practical value. For instance, presenting examples of successful large-scale or pilot project implementations would be beneficial.

2. The environmental benefits of biochar-based catalysts are well-articulated. However, a more thorough exploration of the biochar production process's lifecycle assessment (LCA), including its carbon footprint and sustainability implications, is warranted. Furthermore, a discussion on the commercial scalability of these processes would be advantageous.

3. The conclusion would be strengthened by providing more specific future research directions. Identifying key areas for further study, such as enhancing catalyst stability or developing more efficient machine learning models, would offer readers a clearer roadmap for advancing this technology.

Responses to Reviewers' Comments

Overall Comments:

We thank the editor and reviewers for their comments and suggestions that helped us to improve this manuscript. We have streamlined the abstract to meet the 150-word limit. We provide our responses to all of the reviewers' comments as well as our corrective actions below.

Responses to Reviewer 3:

Comment 1. Specifically, a more in-depth comparison with existing commercial catalytic methods is necessary, particularly regarding scalability and efficiency. Emphasizing the potential improvements and advancements offered by biochar-based catalysts would strengthen the manuscript's contribution to the field.

Response: Thank you for your comments. We fully agree with you that a comprehensive comparison between biochar-based catalysts and existing commercial catalysts is essential in the field of catalytic conversion of plastic waste into fuels, especially in terms of scalability and efficiency. The following discussion highlights the major advantages and potential improvements offered by biochar-based catalysts:

1.Scalability

Biochar-based catalysts are derived from biomass waste materials, which are abundant and readily available. This provides a significant edge in scalability compared to traditional commercial catalysts that often rely on limited or expensive resources. For example, biochar is commonly produced from agricultural residues, forestry waste, or even municipal solid waste, ensuring a sustainable and cost-effective supply chain. In contrast, conventional catalysts such as zeolite or metal-based catalysts may face limitations, mainly due to the finite availability of raw materials and high production costs. The wide availability of biomass feedstocks for biochar production aligns well with the principles of circular economy and sustainability, making biochar-based catalysts a promising alternative for large-scale applications.

2. Efficiency

Biochar-based catalysts exhibit several properties that enhance their catalytic efficiency in the conversion of plastic waste into fuels. They possess high specific surface areas and abundant pore structures, which facilitate efficient mass transfer and increase the accessibility of active sites. This leads to improved reaction rates and high yields of valuable products such as liquid fuels. Additionally, biochar's surface characteristics provide excellent resistance to coking at high temperatures, thereby extending the catalyst's lifetime, compared to traditional metal catalysts that are prone to deactivation. Through surface modification techniques, such as metal-loading or acid treatment, biochar-based catalysts can be tailored to optimize product distribution and selectivity, further enhancing their performance in the catalytic conversion process.

3. Potential Improvements and Advantages

Biochar-based catalysts offer several potential improvements and advantages over existing commercial catalysts in the field of plastic waste conversion. Their raw materials are renewable and sustainable, which aligns with the growing demand for environmentally friendly technologies. Moreover, biochar-based catalysts are chemically modified to enhance their performance for specific reactions, such as improving the yield of high-value fuels or reducing the formation of unwanted by-products. The ability to combine biochar-based catalysts with other advanced technologies, such as plasma-assisted catalysis or photocatalysis, further expands their application scopes and efficiencies. Overall, biochar-based catalysts not only provide a cost-effective and sustainable solution but also demonstrate superior performance in terms of catalytic activity, selectivity, and resistance to deactivation, making them a valuable advancement in the field of plastic waste conversion.

Thus, to address this comment, we added the following sentences into Section 3 of this manuscript:

Currently, common commercial catalysts used in the field of converting plastic waste into fuels include zeolite catalysts (such as ZSM-5), metal oxide catalysts (such as V_2O_5 and Fe_2O_3), noble metal catalysts (such as Pt and Pd), and activated carbon catalysts. These catalysts are widely used due to their high catalytic performance and mature technologies, but they also face issues such as high costs, limited resources, high energy consumption during production, and susceptibility to coking and deactivation. In contrast, the use of biochar as a catalyst offers several merits, specifically its feasible production from low-cost, readily available biomass resources, and its mitigation of adverse environmental impacts caused by biomass mismanagement [76, 77]. The BBCs are thermally and mechanically stable, chemically inert, and biodegradable. In addition, it improves metal-carrier interactions between metal and carbon by templating, chemical activation, metal impregnation, or heteroatom doping[78]. It is regenerative, inexpensive, and adaptable for continued effective operation at high temperatures. Therefore, compared to expensive metal *catalysts, biochar is a lower-cost and more sustainable catalytic material* [79]*, making them a strong alternative to traditional commercial catalysts.*

Comment 2. The abstract and introduction effectively establish the manuscript's foundation. However, the specific research gaps addressed by this review require clearer definition. Explicitly articulating the limitations of current technologies and demonstrating how biochar-based catalysts can overcome them would enhance the reader's understanding of the study's significance.

Response: In the field of catalytic conversion of plastic waste into fuels, existing technologies face several bottlenecks, while biochar-based catalysts offer significant advantages in addressing these challenges:

Existing technological bottlenecks are addressed as follows:

Low Conversion Efficiency and Selectivity. Traditional powder catalysts used in plastic waste pyrolysis often suffer from low carbon-hydrogen conversion rates and poor product selectivity. For example, when processing polystyrene, these catalysts typically achieve low carbon and hydrogen recovery rates, making it difficult to efficiently convert plastic waste into high-value fuels or chemicals.

Catalyst Stability and Reusability. Traditional catalysts are prone to coking and deactivation during high-temperature pyrolysis, and they are often not reusable. For instance, powder catalysts experience a significant decline in catalytic efficiency after multiple uses, which limits their application in large-scale industrial processes.

Environmental and Economic Costs. Existing technologies often involve high costs and significant greenhouse gas emissions. Noble metal catalysts, though highly efficient, are expensive and scarce. Additionally, traditional catalytic processes may require high energy inputs, further exacerbating environmental and economic concerns.

And the advantages of biochar-based catalysts are discussed as follows:

High Conversion Efficiency and Product Selectivity. Biochar-based catalysts, especially when modified (e.g., with metal loading or defect site introduction), can significantly enhance the conversion efficiency and product selectivity of plastic waste. For example, in microwave-assisted co-pyrolysis of biomass and plastic waste using biochar-based catalysts, the yield of aromatics can reach up to 74.13%, while significantly reducing the formation of oxygenated compounds[1].

Environmental Friendliness and Sustainability. Biochar-based catalysts are derived from biomass waste, which is abundant and renewable. Their production and use are relatively green and sustainable. Moreover, these catalysts exhibit good resistance to coking, extending their service life and reducing environmental impacts.

Economic Viability and Reusability. Biochar-based catalysts are cost-effective and can be easily regenerated and reused through simple physical or chemical methods. For example, a modified multi-layer stainless steel metal-based catalyst combined with biochar technology, developed by Southeast University, not only achieves efficient conversion of plastic waste but also allows for multiple cycles of catalyst reuse through ultrasonic separation techniques.

Multifunctionality and Synergistic Effects. Biochar-based catalysts can be used not only for the pyrolysis of plastic waste but also for co-processing with biomass, further enhancing the value of the products. For instance, in the co-pyrolysis of biomass and plastic waste, biochar-based catalysts promote radical reactions, increasing the yields of synthesis gas and aromatics.

In summary, biochar-based catalysts offer significant advantages in addressing the bottlenecks of existing plastic waste conversion technologies. They improve conversion efficiency, reduce environmental costs, and enhance economic sustainability, providing a promising technological pathway for the high-value utilization of plastic waste. To address this comment, we have added the following sentences to Section 7 in this manuscript:

In the field of catalytic conversion of plastic waste, existing technologies face numerous bottlenecks. Traditional catalysts used in pyrolysis often exhibit low conversion efficiency and selectivity, are prone to coking and deactivation, and are typically not reusable. Moreover, these conventional technologies are associated with high costs and significant greenhouse gas emissions. In contrast, biochar-based catalysts demonstrate significant advantages. After modification (e.g., by loading metals or introducing defect sites), biochar catalysts can significantly enhance the conversion efficiency and product selectivity of plastic waste. For example, in microwave-assisted co-pyrolysis of biomass and plastic waste, biochar-based catalysts can achieve an aromatic yield of up to 74.13% while reducing the formation of oxygenated compounds157. Biochar-based catalysts are derived from abundant biomass waste, making their production and use green and sustainable. They also exhibit good resistance to coking, which extends their service life. These catalysts are cost-effective and can be easily regenerated and reused through simple physical or chemical methods. Additionally, they possess multifunctionality and synergistic effects, *such as promoting radical reactions in co-pyrolysis with biomass to increase the yields of synthesis gas and aromatics, thereby further enhancing the value of the products. In summary, biochar-based catalysts offer a highly promising technological pathway for the high-value utilization of plastic waste. They effectively address the bottlenecks of existing technologies and are likely to become one of the most potential candidates for future commercial catalysts.*"

Comment 3. While the review comprehensively covers biochar activation and modification methods, including machine learning-guided optimization, the inclusion of experimental data or case studies would enhance its practical value. For instance, presenting examples of successful large-scale or pilot project implementations would be beneficial.

Response: Currently, biochar-based catalysts in pyrolysis and gasification of plastic waste into energy chemicals have made significant progress in research and are gradually transitioning from laboratory studies to pilot-scale and small-scale applications.

Laboratory studies have demonstrated that biochar-based catalysts can achieve high catalytic efficiency and product selectivity. In pilot-scale applications, biochar-based catalysts are also being scaled up. For example, Panjin Sanli Zhongke New Materials Co., Ltd., is conducting a pilot project with an annual capacity of 400 tons for bio-based furan and catalyst production, including a 100-ton-per-year catalyst production capability[2]. Additionally, in 2013, Professor Xing Xianjun's team from Hefei University of Technology developed a pilot demonstration project for producing 5,000 tons of biochar per year. By optimizing process parameters, they successfully reduced the biomass carbonization time from 7 days to just 1 day. This breakthrough significantly improved production efficiency and laid the foundation for subsequent industrial applications. The team also developed the "solid-solution partial pressure technology," which reintroduced carbon-containing gases generated during the reaction back into the biochar molecules, converting nearly all the carbon elements in biomass into charcoal with a carbon conversion rate of approximately 60%. Additionally, by combining experiments with numerical simulations, the team identified the "critical energy point" for phase transformation during biomass carbonization and designed the optimal catalyst to achieve controllable biochar production. As a result, the biomass carbonization process was further shortened to just 30 minutes, with a significant increase in production efficiency and nearly zero emissions. By the end of 2019, the world's first biochar carbonization furnace with a daily output of 100 tons was successfully developed and put into operation, achieving an annual production capacity of 5,000 tons of biochar[3].

Although biochar-based catalysts are currently mainly used in laboratory and pilot-scale applications, their advantages in cost-effectiveness, environmental friendliness, and catalytic performance make them highly promising for industrial-scale use. Future research directions may include further optimizing catalyst preparation processes, enhancing catalyst stability and reusability, and scaling up production.

Overall, biochar-based catalysts have shown great potential in the pyrolysis and gasification of plastic waste. However, more research and development are needed in process optimization and cost control to achieve large-scale industrial applications. This review comprehensively explores the advantages and disadvantages of biochar catalysis and the challenges it faces. Through an in-depth analysis of these challenges, the review explores the possibilities and limitations of transitioning from laboratory to commercial applications for future research and applications. To address this comment, we added the following sentences to Section 7 in the manuscript:

"*While biochar catalysts have demonstrated significant potential in laboratory settings, their large-scale implementation is constrained by issues related to stability, recyclability, activity optimization, economic feasibility, environmental impact, and mechanistic understanding, which represents opportunities for further research and development.* "

References

1. Wang B, et al. Enhancement of aromatics and syngas production by co-pyrolysis of biomass and plastic waste using biochar-based catalysts in microwave field. Energy 293 (2024) 130711.

2. https://finance.people.com.cn/n1/2024/0805/c1004-40292320.html.

3. http://www.water8848.com/news/202408/05/158245.html.

Comment 4. The environmental benefits of biochar-based catalysts are well-articulated. However, a more thorough exploration of the biochar production process's lifecycle assessment (LCA), including its carbon footprint and sustainability implications, is warranted. Furthermore, a discussion on the commercial scalability of these processes would be advantageous.

Response: Thank you for your constructive suggestions. To address this comment, we added the following sentences to Section 6 of this manuscript:

a) Carbon Footprint and Sustainability Impacts exploration in Subsections 6.1

Life cycle analysis (LCA) is a widely used approach for assessing the environmental impacts of waste management systems and strategies [151]. It is a critical tool for evaluating the environmental impact of biochar production, encompassing the entire process from raw material sourcing, and production, to final application. LCA quantifies the carbon footprint and ecosystem impacts of biochar production, providing potential environmental benefits or disadvantages of various plastic waste recycling and recovery options were assessed by LCA [152]. For instance, biochar produced through biomass pyrolysis can fix approximately 50% of carbon in the soil, achieving long-term carbon sequestration. Research indicates that although biochar production releases certain amounts of greenhouse gases (e.g., CO_2, CH_4, and N_2O), its carbon sequestration capacity can significantly offset these emissions (Fig. 5a-d).

Kolapkar et al. [153] performed LCA of a pilot-scale integrated torrefaction-extrusion technology, which targeted solid fuel pellet production from mixed fibre-plastic waste. The LCA showed that pellets with net negative global warming potential could be produced at this intermediate stage of the life cycle. Azam et al. [154] applied the Institute of Environmental Sciences-Impact Assessment (CML-IA) baseline method to compare the environmental impact results of plastic waste pyrolysis and hydrocracking. Compared to pyrolysis, hydrocracking is more beneficial to curb abiotic depletion and fossil fuel abiotic depletion, delaying global warming potential (GWP) 100a, reducing toxicity in human and ecotoxicity in freshwater aquatic (FAETP) and marine aquatic systems, adjusting the potential of photochemical oxidation, acidification and eutrophication and other environmental impacts (Fig. 5a-d). However, the carbon footprint of biochar production is influenced by multiple factors, including feedstock type, pyrolysis technology, energy sources, and transportation distances. Therefore, optimizing these aspects of the biochar production process is crucial for reducing its carbon footprint.

Moreover, the sustainability impacts of biochar production must be comprehensively assessed. Biochar applications can improve soil structure, enhance soil fertility, and reduce the use of chemical fertilizers, thereby lowering the environmental pressures of agricultural production. However, large-scale biochar production may lead to land-use changes and biodiversity loss. Additionally, water consumption during biochar production needs careful consideration, especially in water-scarce regions. Future research should focus more on the LCA of biochar production, optimizing production *processes, selecting sustainable feedstocks, and improving energy efficiency to minimize environmental impacts.*

b) Commercial discussion including technical, economic and policy challenges in Subsections 6.2

"Despite the promising performance of biochar catalysts in laboratory and pilot-scale studies, their large-scale commercial application faces several challenges. First, the economic viability of biochar production is a key factor for commercialization. Currently, biochar production is relatively costly, primarily due to feedstock collection, transportation, and the operation and maintenance of pyrolysis equipment. Optimizing production processes, enhancing equipment efficiency, and developing modular pyrolysis units can significantly reduce production costs. Additionally, utilizing agricultural residues or urban organic waste as feedstocks can not only cut costs but also achieve waste valorization. Second, optimizing the performance of biochar catalysts is also crucial for commercial scalability. The catalytic activity and stability of biochar directly affect its application efficiency in catalytic pyrolysis and advanced oxidation technologies. Enhancing biochar performance through metal doping, surface modification, or composite formation with other materials can significantly improve its catalytic properties. Moreover, the application of machine learning technologies offers new insights into the design and optimization of biochar catalysts. Finally, policy support and market demand are essential for the commercial scalability of biochar catalysts. Many countries and regions have introduced policies to support biochar applications, including carbon taxes, subsidies, and regulations. These policies not only promote the market penetration of biochar but also drive the development and innovation of related technologies. However, market awareness and acceptance of biochar need to be further improved, especially in the energy and environmental sectors. "

" In summary, biochar catalysts hold significant potential in environmental management and sustainable development. However, their life cycle assessment and commercial scalability require further investigation. By optimizing production processes, reducing the carbon footprint, enhancing economic viability, and strengthening policy support, biochar catalysts can be successfully commercialized. Future research should focus on the following aspects: (1) refining the LCA of biochar production to comprehensively quantify its carbon footprint and environmental impacts; (2) improving the performance of biochar catalysts to enhance their application efficiency in catalytic pyrolysis and advanced oxidation technologies; and (3) strengthening policy support and market promotion to raise awareness and acceptance

of biochar. Through these efforts, biochar catalysts can play a vital role in achieving carbon neutrality and sustainable development goals."

Comment 5. The conclusion would be strengthened by providing more specific future research directions. Identifying key areas for further study, such as enhancing catalyst stability or developing more efficient machine learning models, would offer readers a clearer roadmap for advancing this technology.

Response: The potential of biochar-based catalysts in catalytic pyrolysis and advanced oxidation technologies has been widely recognized. However, as highlighted by your insightful comments, a more specific roadmap for future research is necessary to address the limitations and advance this technology. Below, we provide a detailed outlook on key areas that require further investigation, focusing on overcoming current challenges and enhancing the applicability of biochar catalysts.

1. Enhancing Catalyst Stability

One of the primary limitations of biochar catalysts is their stability under harsh reaction conditions, such as high temperatures and prolonged exposure to reactive species. Future research should focus on developing biochar catalysts with enhanced structural integrity and resistance to degradation. This can be achieved through:

- **Advanced Material Engineering**: Utilizing techniques such as carbonization at higher temperatures, incorporation of inorganic stabilizers, or the development of biochar composites with robust materials like metal oxides or zeolites.
- **Surface Modification**: Applying surface treatments to introduce functional groups that can enhance the thermal stability and resistance to chemical attack.

2. Improving Recyclability and Reusability

The economic viability of biochar catalysts is significantly impacted by their recyclability and reusability. Research should aim to:

- **Develop Efficient Separation Techniques**: Design methods to easily separate biochar catalysts from reaction products and impurities, ensuring minimal loss of catalytic activity.

- **Enhance Catalyst Durability**: Investigate modifications that prevent catalyst deactivation, such as coating biochar with protective layers or optimizing the pore structure to minimize fouling.

3. Optimizing Catalytic Activity and Selectivity

To maximize the efficiency of biochar catalysts, future studies should focus on:

- **Advanced Modification Strategies**: Exploring novel methods to introduce active sites or enhance existing ones, such as metal doping, plasma treatment, or the use of heteroatoms (e.g., nitrogen, sulfur) to modify biochar surfaces.
- **Machine Learning-Driven Catalyst Design**: Leveraging machine learning algorithms to predict optimal catalyst formulations and reaction conditions, thereby accelerating the discovery of high-performance biochar catalysts.

4. Addressing Economic and Scalability Challenges

For biochar catalysts to achieve widespread commercial adoption, research must address economic and scalability issues:

- **Cost-Effective Production Methods**: Developing scalable and cost-effective biochar production processes, such as continuous pyrolysis systems or the use of low-cost feedstocks like agricultural residues.
- **Process Integration**: Investigating the integration of biochar production with existing industrial processes to reduce costs and enhance overall efficiency.

5. Conducting Comprehensive Life Cycle Assessments (LCA)

A thorough understanding of the environmental impact of biochar production and application is crucial. Future work should include:

- **Detailed LCA Studies**: Conducting comprehensive life cycle assessments to quantify the carbon footprint and environmental impact of biochar production, from feedstock sourcing to end-of-life disposal.
- **Sustainability Metrics**: Developing standardized sustainability metrics to evaluate the overall environmental performance of biochar catalysts, ensuring that they meet global sustainability goals.

6. Mechanistic Understanding and Modeling

A deeper understanding of the catalytic mechanisms underlying biochar performance is essential for rational design and optimization. Future research should:

- **In-Situ Characterization Techniques**: Employ advanced in-situ techniques (e.g., X-ray diffraction, Raman spectroscopy) to monitor structural and chemical changes in biochar catalysts during reactions.
- **Computational Modeling**: Utilize computational methods and molecular simulations to elucidate the active sites and reaction pathways, guiding the design of more efficient biochar catalysts.

Comment 6. In summary, while biochar-based catalysts hold significant promise for catalytic pyrolysis and advanced oxidation technologies, addressing their current limitations is essential for broader application. Future research should focus on enhancing catalyst stability, improving recyclability and reusability, optimizing catalytic activity and selectivity, addressing economic and scalability challenges, conducting comprehensive life cycle assessments, and deepening mechanistic understanding. By targeting these key areas, researchers can provide a clearer roadmap for advancing this technology, ultimately contributing to more sustainable and efficient processes in energy and environmental applications.

Response: Thank you for your valuable insights and suggestions. We believe that by incorporating these future research directions, our review can offer a more comprehensive and forward-looking perspective on the development of biochar-based catalysts. Therefore, we added Section 7 of Opportunities and challenges in this manuscript:

"7. Opportunities and challenges

The future application of biochar-based catalysts in catalytic pyrolysis and advanced oxidation technologies faces several critical challenges that warrant careful consideration from a comprehensive review perspective. While biochar catalysts have demonstrated significant potential in laboratory settings, their large-scale implementation is constrained by issues related to stability, recyclability, activity optimization, economic feasibility, environmental impact, and mechanistic understanding, which represents opportunities for further research and development. Addressing the stability concerns through advanced material engineering and process optimization could significantly enhance the practicality of biochar catalysts. Similarly, improving recyclability and reusability would not only reduce costs but also align with *sustainable development goals. The optimization of catalytic activity and selectivity, driven by innovative modification techniques and data-driven approaches such as machine learning, holds the promise of making biochar catalysts more efficient and versatile.*

Economic and scalability challenges underscore the need for a holistic approach that integrates cost-effective production methods with sustainable resource management. Meanwhile, a thorough life cycle assessment and environmental impact evaluation are crucial for ensuring that the benefits of biochar catalysts outweigh their production costs in terms of both economic and ecological footprints. Finally, a deeper understanding of the catalytic mechanisms will provide a solid foundation for rational catalyst design and process optimization."

Reviewer #4 (Remarks to the Author):

Comment: What are the limitations of biochar-based catalysts for catalytic pyrolysis and advanced oxidation technologies in the future works?

Response: As highlighted by your insightful comments, the future application of biochar-based catalysts in catalytic pyrolysis and advanced oxidation technologies indeed faces several critical challenges that warrant careful consideration from a comprehensive review perspective. While biochar catalysts have demonstrated significant potential in laboratory settings, their large-scale implementation is constrained by issues related to stability, recyclability, activity optimization, economic feasibility, environmental impact, and mechanistic understanding, which represents opportunities for further research and development. Addressing the stability concerns through advanced material engineering and process optimization could significantly enhance the practicality of biochar catalysts. Similarly, improving recyclability and reusability would not only reduce costs but also align with sustainable development goals. The optimization of catalytic activity and selectivity, driven by innovative modification techniques and data-driven approaches such as machine learning, holds the promise of making biochar catalysts more efficient and versatile.

Economic and scalability challenges underscore the need for a holistic approach that integrates cost-effective production methods with sustainable resource management. Meanwhile, a thorough life cycle assessment and environmental impact evaluation are crucial for ensuring that the benefits of biochar catalysts outweigh their production costs in terms of both economic and ecological footprints. Finally, a deeper understanding of the catalytic mechanisms will provide a solid foundation for rational catalyst design and process optimization.

In summary, while the current review acknowledges the limitations of biochar-based catalysts in catalytic pyrolysis and advanced oxidation technologies, it also highlights the vast potential for overcoming these challenges through interdisciplinary research efforts. We are committed to incorporating these considerations into our review, emphasizing the importance of addressing these limitations to advance the field and realize the full potential of biochar catalysts in sustainable energy and environmental applications. We appreciate your valuable feedback and will ensure that our review provides a balanced and forward-looking perspective on this emerging technology.

Based on the above analysis, we have supplemented Section 7-Opportunities and challenges with further analysis of the limitations and future directions of biochar-based catalysts for future work in catalytic pyrolysis and advanced oxidation technologies.