CHEMICAL ENGINEERING TRANSACTIONS

VOL. 83, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-81-5; **ISSN** 2283-9216

DOI: 10.3303/CET2183079

Environmental Performance and Techno-Economic Feasibility of Different Biochar Applications: An Overview

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Biochar has a broad application owning to its physicochemical properties and low cost by origin (by-products or generated from waste). Wide research attention received is the application to the soil as carbon sequestration. In contrast to the efficiency evaluation, the overall cost feasibility and environmental performance of the application still deserves broader analysis and discussion. This study aims to enumerate the advantages, and potential drawbacks of the different applications, in term of cost and the environmental footprints. The other alternatives (e.g. the conventional methods) in achieving the same purpose are compared. Special attention is given to the application of biochar to the soil as carbon sequestration. This study could serve as a guideline in evaluating the pros and cons of biochar application to ensure the unburdening footprints can offset the burdening footprint associated with the generation and other downstream processes towards sustainability.

1. Introduction

The various application of biochar is attributed by its features, including high carbon content, large specific surface area, stable structure, and cation exchange capacity (Wang and Wang, 2019). The characteristics are varying with the types of substrates and the generation methods. The feedstock of biochar can be divided into forestry (e.g. wood), dedicated biomass (e.g. switchgrass) and residues (e.g. corn stover, husk, sawdust) or waste (e.g. food waste). Feedstock with high volatile content generally results in the low biochar yield. Char can be produced via carbonisation processes including pyrolysis, gasification, hydrothermal carbonisation, flash carbonisation or torrefaction as summarised in Figure 1. Biochar yields via the gasification (higher process temperature and different gaseous condition) are usually lower than the pyrolysis process because the gaseous products are the targeted products. The most common process in preparing biochar is pyrolysis and temperature is among the most influential operating parameters (Zhu et al., 2019) affecting the quality and yield of biochar. These including the pH, cation exchange capacity, specific surface area, ash content, volatile matter content, elemental composition and the yield (Li et al., 2019). Zhao et al. (2013) summarised that carbon sequestration, fixed carbon and minerals were determined by feedstock while the pH, specific surface area and recalcitrance were depending by temperature. The other novel pyrolysis methods, including microwave-assisted pyrolysis, co-pyrolysis, wet pyrolysis and pyrolysis with modification have been summarised by Wang et al. (2020).

Bong et al. (2020) suggested that soil amendment and adsorption material are the suitable application for biochar derived from lignocellulosic biomass and food waste. However, the conclusion is mainly on the effectiveness based on physiochemical properties rather than from the environmental and economic perspectives. Modification of biochar to revise the surface properties received significant research interests recently. Huang et al. (2021) review the research efforts on biochar modification to enhance the specific application and cost, focusing on laboratory works instead of mature field application reports. There have been a lot of research and review studies related to improving the properties of biochar for an effective application. Barriers to biochar application in real-world setting deserve more attention, especially the techno-economic

Paper Received: 16/10/2020; Revised: 06/11/2020; Accepted: 15/11/2020
Please cite this article as: Fan Y.V., Klemeš J.J., Lee C.T., 2021, Environmental Performance and Techno-Economic Feasibility of Different Biochar Applications: An Overview, Chemical Engineering Transactions, 83, 469-474 DOI:10.3303/CET2183079

challenges and the undesirable adverse environmental consequences. Tan (2016) highlighted that it remains uncertain whether biochar as carbon sequestration is scalable and cost-effective to mitigate climate change. Belmonte et al. (2017) proposed process system engineering to facilitate the planning of large-scale biochar system. The potential disadvantages of biochar application to the soil include albedo effect due to soil darkening, excessive pH elevation, and degrading the soil quality due to contaminants such as heavy metals. There are still conflicting opinions in the scientific literature regarding the sustainability of biochar. This study aims to enumerate the advantages, and potential drawbacks, in term of cost and the environmental footprints, of different biochar application.

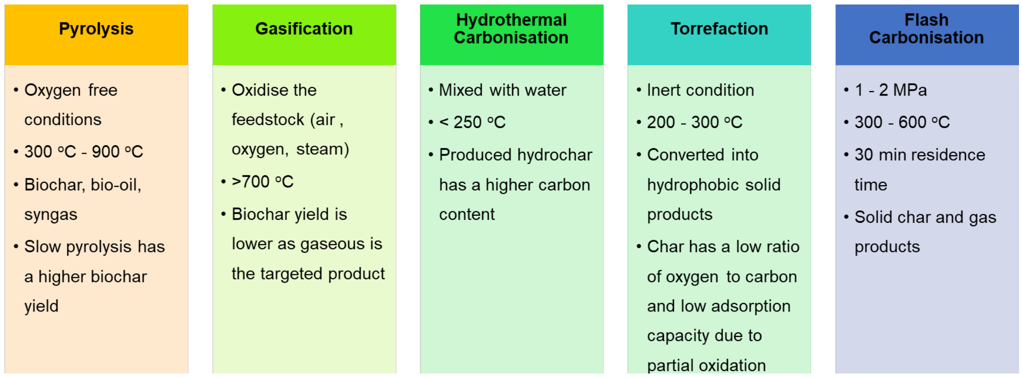

Figure 1: Different thermochemical conversion methods for biochar/char generation. Information extracted from Wang and Wang (2019).

2. Potential uses

The development of biochar has received research attention and application in different fields including environment, energy, agriculture and materials. Figure 2 summarised the potential uses of biochar and different approaches to enhance effectiveness. Different researchers have studied structure-application relationships. For effective absorbent (water and air pollutants), high specific surface area, pore fraction and functional groups on its surface are important. The adsorption capacity depends on raw material, pyrolysis process and solution pH (Cha et al., 2016). One of the issues which limit the large-scale application of biochar as absorbent (e.g. wastewater treatment) is the subsequent separation. Magnetic biochar is introduced to enable the application of biochar in environmental remediation (Yi et al., 2020), facilitating the separation.

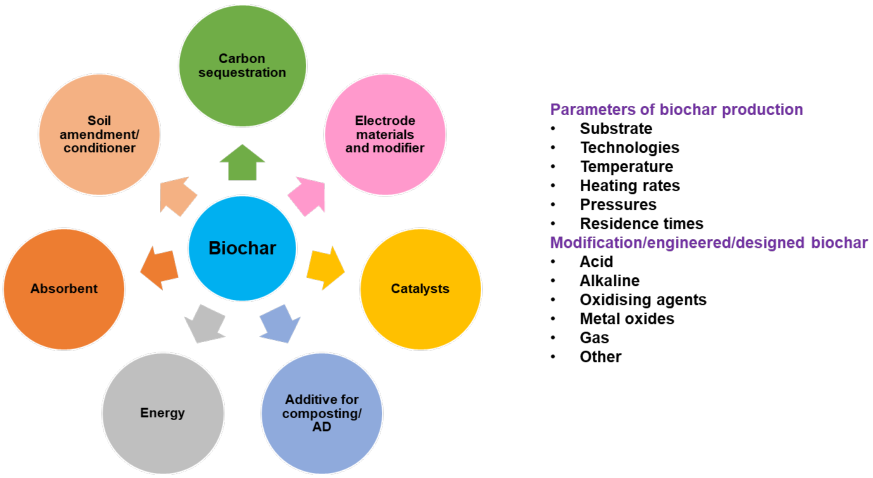

Figure 2: Potential uses of biochar and the approaches to enhance the effectiveness

Biochar has been often modified to revise its surface properties, so the performance of specific application with modified biochar can be enhanced at a reduced cost. The modification methods including acid, alkaline, oxidising agents, metal oxides and steam/gas are to remove impurities, increase surface area/porosity or introduce certain functional groups (hydroxyl, carboxyl) onto biochar surface (Huang et al., 2021). Mašek et al.

(2019) reported that potassium doping on biochar could increase carbon sequestration. Other than the pre- and post-treatment, CO_2 looping in pyrolysis could also enhance the biochar properties (higher specific surface area) (Shen et al., 2017). Xiang et al. (2020) highlighted that engineered biochar is critical in improving the effectiveness of environmental protection, but low-cost modification technology is yet to be developed. Most of the application is still limited to laboratory scale and remains a challenge to perform upscale.

3. The sustainability of biochar application

The applicability of biochar in the various area has been well proven. However, sustainability remains uncertain with no consensus. Table 1 shows the sustainability performance for some of the biochar application. The selected studies show positive impacts in term of sustainability performance; however, it is not questionable. The comparison basis is critical. The cost and environmental feasibility of biochar as activated carbon are generally promising; however, more in-depth comparison to the activated carbon generated from waste is required. Application of functionalised biochar should be given priority in future research (Lu et al., 2020). In general, it can be suggested that an application that focuses on the uses of functional group and surface area (activated carbon, materials, absorbent, catalyst, additives) of biochar is generally feasible.

Table 1: The sustainability performance of the selected biochar application

Biochar Application	Sustainability	Remarks	Reference
To produce activated carbon	• The lowest in cost and environmental footprint compared to biochar as a soil amendment or to displace coal	• The cost and environmental footprint of activated carbon from biochar are not compared to the activated carbon which could produce from another waste stream	Kulas et al. (2019)
	• −0.9 kg CO_2eq/kg and 6.6 kg CO_2eq/kg for biochar and activated carbon • Cost of biochar (200 USD/kg) lower than activated carbon (1,240 USD/kg) to adsorb chromium and zinc, comparable to adsorb lead and copper.	• Considered only the environmental impacts of energy demand • Biogenic carbon and potential soil fluxes are not accounted	Alhashimi and Aktas (2017)
For wastewater treatment	• Low adsorption capacity wood biochar had more benefits for global warming, respiratory effects, and non-carcinogenic. • However, it exhibited higher impacts than powdered activated carbon in eutrophication, carcinogenic, ecotoxicity, acidification, ozone depletion due to higher biochar dose requirements to reach the treatment objective.	• Economic feasibility is not assessed • The compared powdered activated carbon is coal-based	Thompson et al. (2016)
To improve agriculture activities	• Scenario with a higher increase in grain yield (+0.18 to +1.00 t/ha/y) shows the positive net present value (NPV). • However, when the increase in yield is in the range of +0.07 to +0.28 t/ha/y, the NPV is negative even when the benefits time span was indefinitely stretched.	• The estimated increase in crop yield is critical • Depend on the type of crop, efficiency of biochar, longevity of agronomic benefits and optimal application rate.	Dickinson et al. (2015)
Enhance anaerobic digestion (AD)	• 3.60 - 4.10 €/ L for enzyme, 13-16 €/L for nutrients, 0.6 - 20 USD/kg for activated carbon, 0.2 - 0.5 USD/kg for biochar • Less environmental impacts than the conventional AD improvers	• The efficiency of different alternatives are not assessed in detail	Chiappero et al. (2020)

However, the assessment results for soil amendment, carbon sequestration and energy generation have a contradiction. Sustainability of biochar as a carbon soil conditioner/soil amendment and carbon sequestration is still ambiguous, and the efficacy is rather a long term. Dickinson et al. (2015) highlighted that when the increase in crop yield is 0.07 to 0.28 t/ha/y, the net present value is negative no matter how the benefits time span extended significantly. Lu et al. (2020) suggested that a better understanding of structure elucidation, reactivity of biochar, precise functioning as well as evaluation of long-term field application are required. This evaluation is critical as without the sufficient understanding and in-depth assessment; the techno-economic and environmental assessment could not be representative due to inaccurate or non-representative functional unit. Lee et al. (2020) found that the use of biochar for energy is favourable in term of carbon abatement. However, if the indirect land use, addition fertiliser application or biogenic carbon (Fan et al., 2020a) are considered, it could reverse the potential abatement. The sustainability of biochar application as energy also depends on the selected baseline scenario. Homagain et al. (2016) suggested that without the carbon credit accounted from carbon sequestration of biochar, bioenergy alone could not provide an economical alternative to fossil fuel energy production. Fan et al. (2020b) suggested that pyrolysis for energy (biochar to energy) is generally more preferable in term of emission-cost performance unless the biochar (biochar to soil) can be used as a soil amendment, beyond carbon sequestration. Table 2 further presents the different results reported on the sustainability of biochar applied to soil as carbon sequestration. Based on Table 2, the effect of biochar to the soil is generally positive. However, most of the studies have focused on a specific issue, and the comparison basis is not standardised. An assessment which provides a complete picture considering the entire life cycle assessment is still lacking. When life cycle assessment is conducted, some of the sources of environmental footprint, e.g. fluxes, biogenic carbon, land-use change and the life cycle cost is not considered. The sustainability under the different circumstance is yet to be confirmed. Table 3 shows the cost feasibility of biochar production reported in the selected studies. There are cases where biochar production is reported as economically feasible (+).

Table 2: The impact of biochar application on the soil as carbon sequestration

	Remarks	Reference
+	Decrease CH_4 (132 %), increase soil organic carbon sequestration (16 %), increase corn yield (7.4 %)	Yang et al. (2020)
+	Enhance carbon utilisation by soil microbial community and soil organic carbon sequestration of paddy soils	Liu et al. (2019)
+	Increase soil inorganic content by 7.8-62.3 % (Long term application, 20 – 90 t ha^{-1})	Dong et al. (2019)
+	More effective in sequestration soil carbon compared to crop residues	Majumder et al. (2019)
+	Suppressing N_2O and CH_4 emission (21.7 - 62.3 %) in the rice paddy soils	Sun et al. (2019)
+	Decrease soil N_2O fluxes by 30.92 %	He et al. (2017)
-	Increase soil CO_2 fluxes by 22.14 % (suppressed when biochar added to fertilised soil)	He et al. (2017)
+	Have useful negative emission potential (0.7 Gt/y)	Smith (2016)

Table 3: Cost feasibility of biochar production

	Description	Reference
N/A	Slow pyrolysis to biochar pathway required a lower carbon price (subsidy). More financially attractive than fast pyrolysis (fuels and electricity route).	Frank et al. (2020)
N/A	Profitable when the price of CO_2 avoided is at a minimum of 85.76 USD/t to 118.13 USD/t	Thengane et al. (2020)
N/A	Production cost range from 75 - 1,272 $/t of biochar depends on biomass type and technology. 0.05 – 0.15 $/m^2 for soil application	Struhs et al. (2020)
-	Auger based pyrolysis (biochar and biofuel production): 68% of outcomes resulted in financial loss, NPV of -24.3 x 10^6 $. However, if Renewable Identification Numbers credits of biofuel generation are considered, the likelihood of financial loss can be reduced to 50 %	Campbell et al. (2018)
+	Hearth based pyrolysis (biochar with no liquid fuel): NPV of 41.5 x 10^6 $, 20 % likelihood resulting in a net loss	Campbell et al. (2018)
+	Biochar-based bioenergy system with biochar land application offers a 5 - 9 % return on investment, breakeven at about 12-13 y	Homagain et al. (2016)

In some cases, it is either not feasible (-) or assessed, but comparative studies (N/A) is not conducted. Homagain et al. (2016) stated that pyrolysis process accounts for the highest share (36 %) of the total production cost, followed by land application (14 %), feedstock collection (12 %) and transportation cost (9 %). The cost of land application plays a critical role. Struhs et al. (2020) highlighted that capital and operating costs of pyrolysis is relatively stable (lowest sensitivity impact), however biochar selling price and biomass management is critical serving as influencing factors for the overall cost feasibility. Carbon pricing and subsidise are also playing an important role, as reported in Thengane et al. (2020).

4. Conclusions

This overview suggests observations as below:

(i) The sustainability of biochar application as activated carbon, materials, absorbent, catalyst and additives are generally favourable. However, it also depends on the selected baseline scenarios. Efficiency is one of the critical factors in enhancing the sustainability of the biochar application that make use of the surface area and functional group. Engineered biochar is an essential field of study.

(ii) The sustainability of biochar application as an energy source and to the soil, e.g. for carbon sequestration is relatively controversial, especially as the carbon intensity of current energy source is lower. Non-CO_2 footprints, application cost and low carbon pricing are the key factors that could overturn the sustainability for the biochar application to soil.

Comprehensive and systematic assessment for a sustainable biochar application is still lacking. Definition of a baseline scenario for a fair comparison is challenging, and a standardise life cycle framework consider different source of an environmental footprint (Čuček et al., 2012) is required.

Acknowledgements

The financial support from the EU supported project Sustainable Process Integration Laboratory – SPIL funded as project No. CZ.02.1.01/0.0/0.0/15_003/0000456, by Czech Republic Operational Programme Research and Development, Education, Priority 1: Strengthening capacity for quality research under the collaboration agreement with Universiti Teknologi Malaysia is acknowledged.

References

Alhashimi H. A., Aktas C. B., 2017, Life cycle environmental and economic performance of biochar compared with activated carbon: a meta-analysis, Resources, Conservation and Recycling, 118, 13-26.

Belmonte B. A., Benjamin M. F. D., Tan R. R., 2017, Biochar systems in the water-energy-food nexus: the emerging role of process systems engineering, Current Opinion in Chemical Engineering, 18, 32-37.

Bong C.P., Lim L.Y., Lee C.T., Ong P.Y., Klemeš J.J., Li C., Gao Y., 2020, Lignocellulosic biomass and food waste for biochar production and application: A review, Chemical Engineering Transactions, 81, 427-432.

Campbell R.M., Anderson N.M., Daugaard D.E., Naughton H.T., 2018, Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty, Applied Energy, 230, 330-343.

Cha J.S., Park S.H., Jung S.C., Ryu C., Jeon J.K., Shin M.C., Park Y.K., 2016, Production and utilisation of biochar: A review, Journal of Industrial and Engineering Chemistry, 40, 1-15.

Chiappero M., Norouzi O., Hu M., Demichelis F., Berruti F., Di Maria F., Mašek O., Fiore S., 2020, Review of biochar role as additive in anaerobic digestion processes, Renewable and Sustainable Energy Reviews, 131, 110037.

Čuček L., Klemeš J.J., Kravanja Z., 2012, A review of footprint analysis tools for monitoring impacts on sustainability, Journal of Cleaner Production, 34, 9-20.

Dickinson D., Balduccio L., Buysse J., Ronsse F., Van Huylenbroeck G., Prins, W., 2015, Cost-benefit analysis of using biochar to improve cereals agriculture, GCB Bioenergy, 7(4), 850-864.

Dong X., Singh B.P., Li G., Lin Q., Zhao X., 2019, Biochar increased field soil inorganic carbon content five years after application, Soil and Tillage Research, 186, 36-41.

Fan Y.V., Klemeš J.J., Ko C.H., 2020a, Bioenergy carbon emissions footprint considering the biogenic carbon and secondary effects, International Journal of Energy Research, DOI: 10.1002/er.5409

Fan Y.V, Tan R.R., Klemeš J.J., 2020b, A system analysis tool for sustainable biomass utilisation considering the Emissions-Cost Nexus, Energy Conversion and Management, 210, 112701.

Frank J.R., Brown T.R., Malmsheimer R.W., Volk T.A., Ha H., 2020, The financial trade-off between the production of biochar and biofuel via pyrolysis under uncertainty, Biofuels, Bioproducts and Biorefining, 14(3), 594-604.

He Y., Zhou X., Jiang L., Li M., Du Z., Zhou G., Shao J., Wang X., Xu Z., Bai S.H., Wallace H., Xu C., 2017, Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis, GCB Bioenergy, 9(4), 743-755.

Homagain K., Shahi C., Luckai N. Sharma M., 2016, Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada. Forest Ecosystems, 3(1), 21.

Huang W.H., Lee D.J., Huang C., 2021, Modification on biochars for applications: A research update, Bioresource Technology, 319, 124100.

Kulas D., Winjobi O., Zhou W., Shonnard D., 2018, Effects of coproduct uses on environmental and economic sustainability of hydrocarbon biofuel from one-and two-step pyrolysis of poplar, ACS Sustainable Chemistry & Engineering, 6(5), 5969-5980.

Lee M., Lin Y.L., Chiueh P.T., Den W., 2020, Environmental and energy assessment of biomass residues to biochar as fuel: A brief review with recommendations for future bioenergy systems, Journal of Cleaner Production, 251, 119714.

Li S., Harris S., Anandhi A., Chen G., 2019, Predicting biochar properties and functions based on feedstock and pyrolysis temperature: A review and data syntheses, Journal of Cleaner Production, 215, 890-902.

Liu Z., Zhu M., Wang J., Liu X., Guo W., Zheng J., Bian R., Wang G., Zhang X., Cheng K., Liu X., Li L., Pan G., 2019. The responses of soil organic carbon mineralisation and microbial communities to fresh and aged biochar soil amendments, GCB Bioenergy, 11(12), 1408-1420.

Lu L., Yu W., Wang Y., Zhang K., Zhu X., Zhang Y., Wu Y., Ullah H., Xiao X., Chen B., 2020. Application of biochar-based materials in environmental remediation: from multi-level structures to specific devices. Biochar, 2(1), 1-31.

Majumder S., Neogi S., Dutta T., Powel M.A., Banik P., 2019, The impact of biochar on soil carbon sequestration: Meta-analytical approach to evaluating environmental and economic advantages, Journal of Environmental Management, 250, 109466.

Mašek O., Buss W., Brownsort P., Rovere M., Tagliaferro A., Zhao L., Cao X., Xu G, 2019, Potassium doping increases biochar carbon sequestration potential by 45 %, facilitating decoupling of carbon sequestration from soil improvement, Scientific Reports, 9(1), 1-8.

Shen Y., Ma D., Ge X., 2017, CO_2-looping in biomass pyrolysis or gasification, Sustainable Energy & Fuels, 1(8), 1700-1729.

Smith P., 2016, Soil carbon sequestration and biochar as negative emission technologies, Global Change Biology, 22(3), 1315-1324.

Struhs E., Mirkouei A., You Y., Mohajeri A., 2020, Techno-economic and environmental assessments for nutrient-rich biochar production from cattle manure: A case study in Idaho, USA, Applied Energy, 279, 115782.

Sun H., Lu H., Feng Y., 2019, Greenhouse gas emissions vary in response to different biochar amendments: an assessment based on two consecutive rice growth cycles, Environmental Science and Pollution Research, 26(1), 749-758.

Tan R.R., 2016, A multi-period source–sink mixed integer linear programming model for biochar-based carbon sequestration systems, Sustainable Production and Consumption, 8, 57-63.

Thengane S.K., Kung K., York R., Sokhansanj S., Lim C.J., Sanchez D.L., 2020. Technoeconomic and emissions evaluation of mobile in-woods biochar production, Energy Conversion and Management, 223, 113305.

Thompson K.A., Shimabuku K.K., Kearns J.P., Knappe D.R., Summers R.S., Cook S.M., 2016, Environmental comparison of biochar and activated carbon for tertiary wastewater treatment, Environmental Science & Technology, 50(20), 11253-11262.

Wang J., Wang S., 2019, Preparation, modification and environmental application of biochar: a review, Journal of Cleaner Production, 227, 1002-1022.

Wang L., Ok Y.S., Tsang D.C., Alessi D.S., Rinklebe J., Wang H., Mašek O., Hou R., O'Connor D., Hou, D., 2020, New trends in biochar pyrolysis and modification strategies: feedstock, pyrolysis conditions, sustainability concerns and implications for soil amendment, Soil Use and Management. 36(3),358-386.

Xiang W., Zhang X., Chen J., Zou W., He F., Hu X., Tsang C.W., Ok Y.S., Gao B., 2020, Biochar technology in wastewater treatment: A critical review, Chemosphere, 252, 126539.

Yang W., Feng G., Miles D., Gao L., Jia Y., Li C., Qu Z., 2020, Impact of biochar on greenhouse gas emissions and soil carbon sequestration in corn grown under drip irrigation with mulching, Science of the Total Environment, 729, 138752.

Yi Y., Huang Z., Lu B., Xian J., Tsang E.P., Cheng W., Fang J., Fang Z., 2020, Magnetic biochar for environmental remediation: A review, Bioresource Technology, 298, 122468.

Zhao L., Cao X., Mašek O., Zimmerman A., 2013, Heterogeneity of biochar properties as a function of feedstock sources and production temperatures, Journal of Hazardous Materials, 256, 1-9.

Zhu X., Li, Y., Wang X., 2019, Machine learning prediction of biochar yield and carbon contents in biochar based on biomass characteristics and pyrolysis conditions, Bioresource Technology, 288, 121527.