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Biochar systems in the water-energy-food nexus: the emerging role of process systems engineering

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Biochar application to soil is a potentially scalable carbon management strategy with the capability of achieving negative greenhouse gas emissions. In addition, biochar is also linked to the water-energy-food nexus (WEFN) through its potential to modify soil properties to improve agricultural productivity. Potential benefits include increased yield and reduced demand for water, fertilizers and other inputs. However, the current literature on biochar is highly fragmented, with a significant research gap in system-level analysis to synchronize production, logistics and application into a sustainable carbon management strategy. Process systems engineering (PSE) can provide a framework to allow the potential benefits of biochar systems to be optimized. This article gives an overview of biochar as a strategy to address carbon management and WEFN issues, reviews relevant scientific literature, analyzes bibliometric trends, and maps potential areas for the application of PSE to the planning of large-scale biochar systems.

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Introduction

Steady population growth coupled with rising standards of living is increasing the global consumption of food, water and energy, which in turn contributes to the rising CO_2 concentration in the atmosphere [1,2•,3,4]. These trends have placed pressure on the planet's sustainability limits, especially with respect to the interdependent issues of climate change, water stress, land use and nutrient cycles [5]. These issues raise the significance that negative emissions technologies (NETs) can play in the water-energy-food nexus (WEFN) [6•,7•]. Integrated biochar systems are among the NETs that have potential for scale up due to their reliance on mature technologies. Furthermore, its inherent connection with agro-industrial systems places biochar firmly within the WEFN context [8]. The nexus approach promotes sustainability by considering resources in an integrated manner [9]. The focus of this review is to show how biochar systems can support these three highly interdependent issues in addressing the planet's growing demand for water, food and energy, and help in mitigating climate risks.

Adoption of biochar for environmental management still faces techno-economic challenges and knowledge gaps which hinder deployment. The area of process systems engineering (PSE) can provide quantitative decision-support to aid in the planning of commercial-scale biochar systems [10••]. PSE has evolved from early applications in process design to cover large-scale systems [11•]. The focus on opportunities and challenges for using PSE to plan biochar systems is the distinctive feature of this paper, in contrast to previous reviews which have focused on valorization of biochar for various applications [12]; pyrolysis platforms [13]; effects of feedstock and production conditions on biochar properties [14]; technologies and processing conditions to improve biochar quality for agricultural use [15]; and effects of biochar application on crop productivity [16,17]. This paper, on the other hand, discusses recent trends and future prospects on the role of PSE for planning biochar systems to address WEFN issues.

Biochar is the carbon-rich solid co-product of thermochemical biomass conversion. It consists of labile (degradable) and recalcitrant (unreactive) fractions. The carbon in biochar is derived from atmospheric CO_2 fixed in biomass via photosynthesis. The primary sequestration mechanism of biochar is the stable storage of biochar in soils [18], which makes it a significant carbon management strategy [19].

Biochar can be produced from biomass feedstocks via a range of thermochemical conversion pathways that yield different proportions of biochar, bio-oil and syngas. The properties of these products are dependent on both feedstock and process conditions [20]. Pyrolysis and gasification involve the heating of biomass feedstocks under oxygen-deficient environment, with process conditions optimized to favor formation of desired products [21,22]. Pyrolysis processes are classified into fast and slow pyrolysis [7•]. Slow pyrolysis typically favors the yield of biochar [13,22], while fast pyrolysis generates more bio-oil [7•]. Gasification on the other hand yields syngas that can be used for power generation or as a chemical feedstock for a biorefinery [23].

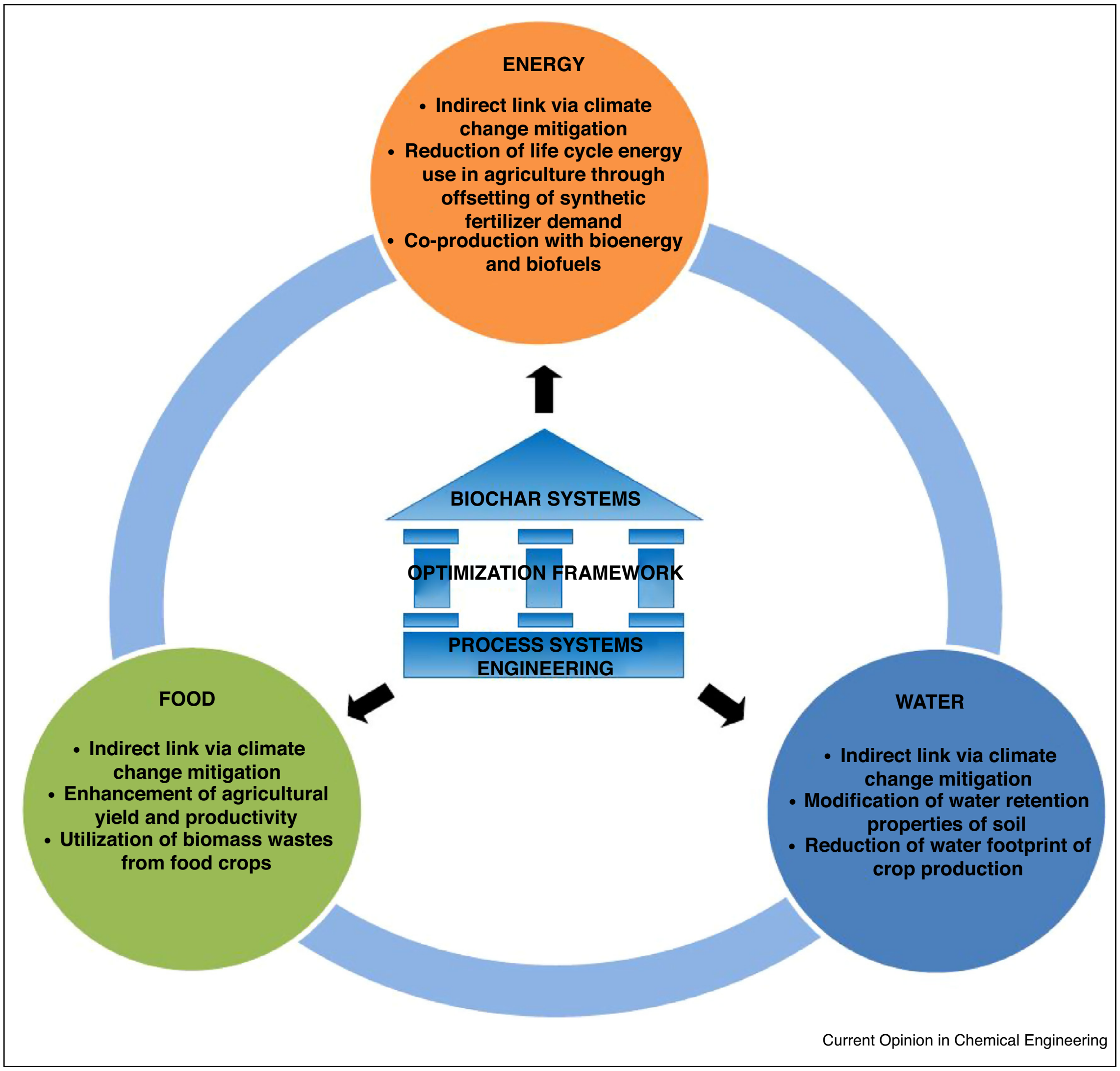
Benefits of biochar to climate and WEFN

Biochar offers several environmental benefits such as carbon sequestration, reduction in greenhouse gas emissions, soil amelioration and crop productivity, water conservation, and supply of green energy. The following subsections describe how biochar systems are linked to the WEFN as illustrated in Figure 1. They also highlight the relevant and recent research findings as summarized in Table 1.

Carbon sequestration and reduction in GHG emissions

Significant interactions exist between water, energy, agriculture and climate [24]. For example, production and use of synthetic fertilizers, which is necessary to secure global food supply, is highly energy intensive and results in significant GHG emissions [5,25]. The production of some staple crops has already been affected by changes in climatic conditions, for example through changes in precipitation patterns, rising sea levels or infestation by new pests and diseases. Energy production and use will be affected by a temperature increase, extreme weather events and changing precipitation patterns [26]. Recent works suggest that it is necessary to approach near-zero

Figure 1



Summary of the main concepts of biochar systems in WEFN. Biochar systems can support the WEFN and PSE is highly leveraged to facilitate the careful planning and implementation of biochar-based systems on a globally significant scale.

Table 1

Relevant research on biochar with direct or indirect link to WEFN.

Environmental benefits	Relevant findings/concepts	References
Climate change mitigation	MSTP of biochar is estimated at 130 Gt CO_2-Ce until 2100.	[7•]
	Global emissions reduction potential of biochar for the period 2030–2050 is estimated to be 0.9–3.0 Gt-CO_2/year, at a cost of \$8–300/t-CO_2.	[6•]
	Soil GHG fluxes are suppressed by biochar application.	[31]
Soil amelioration and crop productivity	Biochar application results in increase soil pH and reduced fertilizer requirement.	[33]
	Biochar application on average increased crop productivity.	[17]
	Effect of biochar on crop productivity was more pronounced in acidic soils.	[16]
	Biochar can be customized for specific sink requirements purposes.	[37••]
Water conservation and remediation	Wastewater treated with biochar for the removal of cadmium and lead was utilized for irrigation.	[44]
	Biochar application enhances soil water retention and reduces irrigation requirement.	[42]
Bioenergy production	Unutilized crop waste globally can yield 1.65 GtC/year in biochar.	[52]
	Net negative carbon footprint can be obtained from a polygeneration system with integrated biochar production.	[55]

future carbon emissions in order to stabilize global temperatures [27–29]. Thus, eventually it may become necessary to achieve negative emissions, rather than just reduce existing positive emissions. Woolf *et al.* [7•] evaluate the maximum sustainable technical potential (MSTP) of biochar to mitigate carbon at 130 Gt CO_2-Ce until 2100, wherein 60% is due to direct carbon sequestration. McLaren [6•] estimates the global emissions reduction potential of biochar for the period 2030–2050 to be 0.9–3.0 Gt-CO_2/year, at a projected cost of \$8–300/t-CO_2. Life cycle assessments (LCAs) consistently predict negative carbon footprint per unit of biomass feedstock [19,30]. In addition, soil GHG (i.e. CH_4 and N_2O) fluxes were suppressed when biochar was added to fertilized soils [31,32].

Crop productivity

Biochar can improve global food security through gains in agricultural productivity [17]. Such gains result from modification of soil properties, such as increase in soil–water and nutrient holding capacities that result in improved crop yields [16,33]. A meta-analysis shows that the effect is often due to increase in pH [16]. Other effects include improvement of mechanical properties of hard soils leading to improved plant growth [34]. Synergistic interaction also exists between biochar and chemical fertilizers [35,36]. Despite the positive reports, the effects of biochar on crop yield responses are variable. Pyrolysis conditions and feedstock type also affect the properties of biochar, which can thus be tailored to suit soil conditions [15,37••]. For instance, the production of potassium-enriched biochar through plasma processing of waste biomass has additional advantages of liming, conditioning and carbon sequestration [38]. Examples of properties that can be controlled in this manner are the concentration of selected elements, or the cation exchange capacity (CEC) [37••,38,39,40].

Water conservation and remediation

With population growth and erratic rainfall patterns, provision of clean water becomes increasingly challenging. Biochar has a role to play in the conservation of water resources and wastewater treatment. For instance, applying biochar is the most effective way of increasing the carbon content of soils which in turn increases the water holding capacity, thus, decreasing the need for irrigation [41–43]. In addition, biochar can also be used for purification of water before use [44–46].

Bioenergy production

Production of bioenergy through pyrolysis of waste biomass is becoming more important due to the limitations of first generation biofuels [47,48]. Integrated systems can use biogas and bio-oil for energy purposes while the biochar can be applied to soil [49–51]. The global annual unused crop waste could potentially produce biochar of about 1.65 GtC/year along with biofuels [52]. There are also studies that show the possibility of producing bio-oils as engine fuels and biochar as a by-product [53,54]. Biochar production systems that export deliverable energy are considered to be a carbon-negative energy system [55–57].

Barriers to biochar application

Technical and economic issues exist which can potentially hinder the application of biochar. Adverse unintended consequences and techno-economic challenges are considered barriers to the adoption of biochar for environmental management. These issues are discussed further in the following subsections.

Risk of applying biochar to soil

Published results on long-term biochar amendment studies at field scale, in particular, are vital to assess the long-term implications of biochar application [58•]. Unintended consequences of biochar application include oversupply of nutrients, excessive pH elevation, adverse impacts on germination and soil biological processes, and binding of agrochemicals. Since biochars are often prepared from a variety of feedstocks including waste materials, the potential release of contaminants needs to be adequately addressed before land application. Contaminants that may be present in biochar include salts, heavy metals, polycyclic aromatic hydrocarbons (PAHs), chlorinated hydrocarbons, and dioxins [59,60]. These agronomic and environmental risks thus necessitate the need to strategically match biochar sources with biochar sinks in order to minimize adverse effects [10••].

Techno-economic assessment of biochar systems

Economic benefits for biochar producers and farmers must come along with social and environmental advantages if biochar is to be implemented globally. Galinato *et al.* [61] suggests that biochar soil application can be economically feasible if the market price is low enough and a carbon market exists. Economic viability can be improved through economies of scale or simultaneous generation of valuable co-products [62–64]. However, alternative end uses of biochar compete with soil amendment [65]. Governments can facilitate its use for carbon management via carbon trading schemes, tax incentives and financing support [66].

Systems perspective on biochar and WEFN

The number of related documents to biochar published in the Scopus database has been increasing over the years. This trend suggests that biochar remains to be an interesting topic because it has been receiving growing attention in the scientific world. Most studies focused on agronomic aspects (6.66%), potential to combat climate change (26.53%), or biochar characterization (59.38%). A refined search was further conducted to narrow the topic down to 'Energy' and 'Chemical Engineering' areas. To date, the filtered search generated around 146 papers and among these papers, only nine of them deal with lifecycle assessment and modeling of biochar systems. Only one article [10••] explicitly deals with PSE to aid in planning of biochar-based systems for large-scale carbon sequestration. This result therefore reveals a research gap in decision-making, planning and implementation of biochar systems.

Modeling of integrated biochar systems for carbon sequestration is still in its infancy. Examples include LCA of pyrolysis biochar system (PBS) which reveals higher mitigation potential than direct biomass combustion, subject to economic conditions mentioned previously [67•,68]. The LCA of the GHG balance of the biochar supply chain indicates that the gasification stage had the highest impact in the supply chain [69]. On the other hand, the LCA of bioenergy system using pyrolysis or direct combustion shows that direct combustion has higher energy efficiency [49]. Optimization models have been developed for the integration of biochar production in a polygeneration system with net negative carbon footprint [55] and for the biochar allocation networks for carbon sequestration [10••].

It is clear that systems optimization would be necessary to facilitate careful planning of biochar-based systems. To make biochar amendments more beneficial, biochar properties can be customized in order to suit soil conditions [37••]. This can also minimize the potential for adverse unintended consequences. These approaches can also guide policy formulation and recommendations concerning biochar production and subsequent application to soil.

Conclusions and prospects for future research

Biochar technology can enhance global food security, conserve water resources, and supply green energy. These advantages link biochar to the WEFN and provide a platform for PSE in modeling integrated biochar systems to yield benefits at a significant scale in the future. Future PSE aspects of biochar research include techno-economic analysis via lifecycle costing (LCC) to fully assess the economic viability of biochar production for soil amendment and carbon sequestration, taking into account economic externalities for decision-making [70]. There will be a need for an optimization framework to facilitate planning and implementation of biochar-based systems on a globally significant scale. Optimal design of industrial-scale PBSs is another PSE application area; for example, feedstock and process conditions can be selected to match the biochar sink requirements [37••]. Balancing biochar and bioenergy production along with energy efficiency enhancements in biochar production is another avenue for PSE tools. These measures will be necessary to improve the system-level energy balance profile. Biochar-based networks can be synthesized wherein biochar could be customized in order to fit certain soil conditions; this capability can be integrated as an extension of a previously developed allocation model [10••]. Future work can further put emphasis on the development of multiple-objective extensions taking into account economic aspects as well as various supply chain sustainability metrics [71]. PSE is indeed critical for scaling up biochar systems to become a global strategy that will address the WEFN.

Conflicts of interest

The authors declare no conflict of interest.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Schwarzer S: **Keeping track of our changing environment — from Rio to Rio +20 (1992–2012)**. *Environ Dev* 2012, **3**:166-179.

2. • Garcia DJ, You FQ: **The water-energy-food nexus and process systems engineering: a new focus**. *Comput Chem Eng* 2016, **91**:49-67.

This paper provides an in-depth review of the relevant contributions of PSE to the water energy food nexus and presents future research challenges and gaps in the PSE community regarding modeling the WEFN.

3. International Energy Agency: *World Energy Outlook*. 2012:. France.

4. Food and Agriculture Organization of the United Nations: *Energy-Smart Food for People and Climate*. 2011:. Issue Paper, 2/3/2017.

5. Rockström J, Steffen W, Noone K, Persson A, Chapin FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ *et al.*: **A safe operating space for humanity**. *Nature* 2009, **461**:472-475.

6. • McLaren D: **A comparative global assessment of potential negative emissions technologies**. *Process Saf Environ Prot* 2012, **90**:489-500.

This paper provided a comparison of different NETs including biochar systems.

7. • Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S: **Sustainable biochar to mitigate global climate change**. *Nat Commun* 2010, **1** http://dx.doi.org/10.1038/ncomms1053.

This paper discusses the potential scale of carbon mitigation possible through biochar application to soil.

8. McGlashan N, Shah N, Caldecott B, Workman M: **High-level techno-economic assessment of negative emissions technologies**. *Process Saf Environ Prot* 2012, **90**:501-510.

9. Hettiarachchi H, Ardakanian R: **Managing water, soil, and waste in the context of global change**. In *Environmental Resource Management and the Nexus Approach*. Edited by Hettiarachchi H, Ardakanian R. Springer International Publishing; 2016:1-7.

10. •• Tan RR: **A multi-period source-sink mixed integer linear programming model for biochar-based carbon sequestration systems**. *Sustain Prod Consum* 2016, **8**:57-63.

This is the first paper to address the problem of matching sources and sinks within a biochar-based carbon management network.

11. • Stephanopoulos G, Reklaitis GV: **Process systems engineering: from Solvay to modern bio- and nanotechnology: a history of development, successes and prospects for the future**. *Chem Eng Sci* 2011, **66**:4272-4306.

This paper gives a broad historical perspective of the evolution of PSE from its early roots as a subdiscipline of chemical engineering, to current trends that include planning of large-scale systems.

12. Nanda S, Dalai AK, Berruti F, Kozinski JA: **Biochar as an exceptional bioresource for energy, agronomy, carbon sequestration, activated carbon and specialty materials**. *Waste Biomass Valorization* 2016, **7**:201-235.

13. Laird DA, Brown RC, Amonette JE, Lehmann J: **Review of the pyrolysis platform for coproducing bio-oil and biochar**. *Biofuels Bioprod Biorefining* 2009, **3**:547-562.

14. Xie T, Sadasivam BY, Reddy KR, Wang C, Spokas K: **Review of the effects of biochar amendment on soil properties and carbon sequestration**. *J Hazard Toxic Radioact Waste* 201540150131.

15. Tan Z, Lin CSK, Ji X, Rainey TJ: **Returning biochar to fields: a review**. *Appl Soil Ecol* 2017, **116**:1-11.

16. Jeffery S, Verheijen FGA, van der Velde M, Bastos AC: **A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis**. *Agric Ecosyst Environ* 2011, **144**:175-187.

17. Biederman LA, Harpole WS: **Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis**. *GCB Bioenergy* 2013, **5**:202-214.

18. Lehmann J, Amonette JE, Roberts K: **Role of biochar in mitigation of climate change**. In *Handbook of Climate Change and Agroecosystems — Impacts, Adaptation and Mitigation.* Edited by Hillel D, Rosenzweig C. Imperial College Press; 2011: 755.

19. Field JL, Keske CMH, Birch GL, Defoort MW, Cotrufo MF: **Distributed biochar and bioenergy coproduction: a regionally specific case study of environmental benefits and economic impacts**. *GCB Bioenergy* 2013, **5**:177-191.

20. Luo L, Xu C, Chen Z, Zhang S: **Properties of biomass-derived biochars: combined effects of operating conditions and biomass types**. *Bioresour Technol* 2015, **192**:83-89.

21. Goyal HB, Seal D, Saxena RC: **Bio-fuels from thermochemical conversion of renewable resources: a review**. *Renew Sustain Energy Rev* 2008, **12**:504-517.

22. Brown TR, Wright MM, Brown RC: **Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis**. *Biofuels Bioprod Biorefining* 2011, **5**:54-68.

23. Dasappa S, Subbukrishna DN, Suresh KC, Paul PJ, Prabhu GS: **Operational experience on a grid connected 100 kWe biomass gasification power plant in Karnataka, India**. *Energy Sustain Dev* 2011, **15**:231-239.

24. GRACE Communications Foundation: *The Impact of Climate Change on Water Resources*. 2017 http://www.gracelinks.org/2380/the-impact-of-climate-change-on-water-resources.

25. Razon LF: **Is nitrogen fixation (once again) ‘‘vital to the progress of civilized humanity’’?** *Clean Technol Environ Policy* 2015, **17**:301-307.

26. European Climate Foundation: *Climate Change: Implications for the Energy Sector*. 2013 https://europeanclimate.org/climate-change-implications-for-the-energy-sector/.

27. Matthews HD, Caldeira K: **Stabilizing climate requires near-zero emissions**. *Geophys Res Lett* 2008, **35**:1-5.

28. Solomon S, Plattner GK, Knutti R, Friedlingstein P: **Irreversible climate change due to carbon dioxide emissions**. *Proc Natl Acad Sci U S A* 2009, **106**:1704-1709.

29. Broecker WS: **Climate change: CO_2 arithmetic**. *Science* 2007, **315**:1371.

30. Bartocci P, Bidini G, Saputo P, Fantozzi F: **Biochar pellet carbon footprint**. *Chem Eng Trans* 2016, **50**:217-222.

31. He Y, Zhou X, Jiang L, Li M, Du Z, Zhou G, Shao J, Wang X, Xu Z, Hosseini Bai S *et al.*: **Effects of biochar application on soil greenhouse gas fluxes: a meta-analysis**. *GCB Bioenergy* 2017, **9**:743-755.

32. Awasthi MK, Wang M, Chen H, Wang Q, Zhao J, Ren X, Li D, Awasthi SK, Shen F, Li R *et al.*: **Heterogeneity of biochar amendment to improve the carbon and nitrogen sequestration through reduce the greenhouse gases emissions during sewage sludge composting**. *Bioresour Technol* 2017, **224**:428-438.

33. Duku MH, Gu S, Ben Hagan E: **Biochar production potential in Ghana — a review**. *Renew Sustain Energy Rev* 2011, **15**:3539-3551.

34. Gaskin JW, Speir A, Morris LM, Ogden L, Harris K, Lee D, Das KC: **Potential for pyrolysis char to affect soil moisture and nutrient status of a loamy sand soil**. In *Proceedings of the 2007 Georgia Water Resources Conference*. 2007 http://hdl.handle.net/1853/48168.

35. Chan KY, Van Zwieten L, Meszaros I, Downie A, Joseph S: **Agronomic values of greenwaste biochar as a soil amendment**. *Aust J Soil Res* 2007, **45**:629-634.

36. Viger M, Hancock RD, Miglietta F, Taylor G: **More plant growth but less plant defence? First global gene expression data for plants grown in soil amended with biochar**. *GCB Bioenergy* 2015, **7**:658-672.

37. •• Novak JM, Ippolito JA, Lentz RD, Spokas KA, Bolster CH, Sistani K, Trippe KM, Phillips CL, Johnson MG: **Soil health, crop productivity, microbial transport, and mine spoil response to biochars**. *Bioenergy Res* 2016, **9**:454-464.

This review paper discusses the effective and ineffective uses of biochar and introduces the 'designer biochar' concept as a key strategy to address specific soil deficiencies or problem.

38. Karim AA, Kumar M, Singh SK, Panda CR, Mishra BK: **Potassium enriched biochar production by thermal plasma processing of banana peduncle for soil application**. *J Anal Appl Pyrolysis* 2017, **123**:165-172.

39. Shen Y, Linville JL, Ignacio-de Leon PAA, Schoene RP, Urgun-Demirtas M: **Towards a sustainable paradigm of waste-to-energy process: enhanced anaerobic digestion of sludge with woody biochar**. *J Clean Prod* 2016, **135**:1054-1064.

40. Lee JW, Hawkins B, Li X, Day DM: **Biochar fertilizer for soil amendment and carbon sequestration**. In *Advanced Biofuels and Bioproducts.* Edited by Lee JW. New York: Springer; 2013:57-68.

41. Smith JU, Fischer A, Hallett PD, Homans HY, Smith P, Abdul-Salam Y, Emmerling HH, Phimister E: **Sustainable use of organic resources for bioenergy, food and water provision in rural Sub-Saharan Africa**. *Renew Sustain Energy Rev* 2015, **50**:903-917.

42. Novak JM, Busscher WJ, Watts DW, Amonette JE, Ippolito JA, Lima IM, Gaskin J, Das KC, Steiner C, Ahmedna M *et al.*: **Biochars impact on soil-moisture storage in an ultisol and two aridisols**. *Soil Sci* 2012, **177**:310-320.

43. Streubel JD, Collins HP, Garcia-Perez M, Tarara J, Granatstein D, Kruger CE: **Influence of contrasting biochar types on five soils at increasing rates of application**. *Soil Sci Soc Am J* 2011, **75**:1402-1413.

44. Ziada MEA, Mashaly IA, Elkhalik AFA, El Sherbiny HA: **Utilization of wastewater treated with rice husk biochar for irrigation and production of rice plant**. *J Environ Sci* 2015, **44**:443-453.

45. Kambo HS, Dutta A: **A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications**. *Renew Sustain Energy Rev* 2015, **45**:359-378.

46. Mohan D, Sarswat A, Ok YS, Pittman CU: **Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent — a critical review**. *Bioresour Technol* 2014, **160**:191-202.

47. Harto C, Meyers R, Williams E: **Life cycle water use of low-carbon transport fuels**. *Energy Policy* 2010, **38**:4933-4944.

48. Harvey M, Pilgrim S: **The new competition for land: food, energy, and climate change**. *Food Policy* 2011, **36**:S40-S51.

49. Ericsson N, Sundberg C, Nordberg A, Ahlgren S, Hansson PA: **Time-dependent climate impact and energy efficiency of combined heat and power production from short-rotation coppice willow using pyrolysis or direct combustion**. *GCB Bioenergy* 2017, **9**:876-890.

50. Sigurjonsson HÆ, Elmegaard B, Clausen LR, Ahrenfeldt J: **Climate effect of an integrated wheat production and bioenergy system with low temperature circulating fluidized bed gasifier**. *Appl Energy* 2015, **160**:511-520.

51. Strezov V, Popovic E, Filkoski RV, Shah P, Evans T: **Assessment of the thermal processing behavior of tobacco waste**. *Energy Fuels* 2012, **26**:5930-5935.

52. Lee JW, Day DM: **Smokeless biomass pyrolysis for producing biofuels and biochar as a possible arsenal to control climate change**. In *Advanced Biofuels and Bioproducts.* Edited by Lee JW. New York: Springer; 2013:23-34.

53. Bridgwater T, Sipilä K, Spitzer J, Wilén C: **Editorial**. *Biomass Bioenergy* 2012:38.

54. Saghir M, Siddiqui S, Wirtz U, Hornung A: **Characterization of the products from intermediate pyrolysis of miscanthus and wood pellets: internal combustion engine application**. *Eur. Biomass Conf. Exhib. Proc.* 2013:511-513.

55. Ubando AT, Culaba AB, Aviso KB, Ng DKS, Tan RR: **Fuzzy mixed-integer linear programming model for optimizing a multi-functional bioenergy system with biochar production for negative carbon emissions**. *Clean Technol Environ Policy* 2014, **16**:1537-1549.

56. Lehmann J: **Bio-energy in the black**. *Front Ecol Environ* 2007, **5**:381-387.

57. Lehmann J: **A handful of carbon**. *Nature* 2007, **447**:143-144.

58. • Kuppusamy S, Thavamani P, Megharaj M, Venkateswarlu K, Naidu R: **Agronomic and remedial benefits and risks of applying biochar to soil: current knowledge and future research directions**. *Environ Int* 2016, **87**:1-12.

This paper gives a comprehensive review of positive and negative impacts of biochar application to soil.

59. Kookana RS, Sarmah AK, Van Zwieten L, Krull E, Singh B: **Biochar application to soil:agronomic and environmental benefits and unintended consequences**. In *Advances in Agronomy.* Edited by Sparks DL. Academic Press; 2011:104-143.

60. Kołtowski M, Oleszczuk P: **Toxicity of biochars after polycyclic aromatic hydrocarbons removal by thermal treatment**. *Ecol Eng* 2015, **75**:79-85.

61. Galinato SP, Yoder JK, Granatstein D: **The economic value of biochar in crop production and carbon sequestration**. *School of Economic Sciences Working Paper Series*; *Carbon, NY: 2010:1-23*.

62. Wrobel-Tobiszewska A, Boersma M, Sargison J, Adams P, Jarick S: **An economic analysis of biochar production using residues from Eucalypt plantations**. *Biomass Bioenergy* 2015, **81**:177-182.

63. Maroušek J: **Significant breakthrough in biochar cost reduction**. *Clean Technol Environ Policy* 2014, **16**:1821-1825.

64. Vochozka M, Marouskova A, Vachal J, Strakova J: **Biochar pricing hampers biochar farming**. *Clean Technol Environ Policy* 2016, **18**:1225-1231.

65. Marousek J, Vochozka M, Plachy J, Zak J: **Glory and misery of biochar**. *Clean Technol Environ Policy* 2016, **19**:311-317.

66. Kong SH, Loh SK, Bachmann RT, Rahim SA, Salimon J: **Biochar from oil palm biomass: a review of its potential and challenges**. *Renew Sustain Energy Rev* 2014, **39**:729-739.

67. • Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J: **Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential**. *Environ Sci Technol* 2010, **44**:827-833.

This is the first paper to give a thorough LCA of hypothetical biochar-based carbon management systems.

68. Hammond J, Shackley S, Sohi S, Brownsort P: **Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK**. *Energy Policy* 2011, **39**:2646-2655.

69. Lugato E, Vaccari FP, Genesio L, Baronti S, Pozzi A, Rack M, Woods J, Simonetti G, Montanarella L, Miglietta F: **An energy-biochar chain involving biomass gasification and rice cultivation in Northern Italy**. *GCB Bioenergy* 2013, **5**:192-201.

70. Moreau V, Weidema BP: **The computational structure of environmental life cycle costing**. *Int J Life Cycle Assess* 2015, **20**:1359-1363.

71. Ahi P, Searcy C, Jaber MY: **Energy-related performance measures employed in sustainable supply chains: a bibliometric analysis**. *Sustain Prod Consum* 2016, **7**:1-15.