Energy, economic, and environmental impacts of sustainable biochar systems in rural China

Siming You[a], Wangliang Li[b], Weihua Zhang[c], Hankwon Lim[d], Harn Wei Kua[e], Young-Kwon Park[f], Avanthi Deshani Igalavithana[g], Yong Sik Ok[g,*]

[a]Division of Systems, Power and Energy, James Watt School of Engineering, University of Glasgow, G12 8QQ, UK

[b]CAS Key Laboratory of Green Process and Engineering, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China

[c]School of Environmental Science and Engineering, Sun Yat-Sen University, Guangzhou, 510275, China

[d]School of Energy and Chemical Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Republic of Korea

[e]Department of Building, School of Design and Environment, National University of Singapore, 117566, Singapore

[f]School of Enviornmental Engineering, University of Seoul, Seoul 02504, Republic of Korea

[g]Korea Biochar Research Center, APRU Sustainable Waste Management & Division of Environmental Science and Ecological Engineering, Korea University, Seoul 02841, Republic of Korea

*Corresponding Author: Email: yongsikok@korea.ac.kr

Abstract

Sustainable bioenergy development and utilization have been a part of China's national strategy. Biochar production from biomass is a promising solution to tackle the energy and environmental challenges of rural China such as air pollution, soil contamination and degradation, sustainable agricultural waste management, and climate change. Most of existing studies on pyrolysis in China utilised a heating rate around 15 °C/min and residence time around 30 min and paid less attention to the effects of heating rate and residence time on biochar production than that of temperature. It was reported that small- and medium-scale (a few kW to 3 MW) gasification systems consisting of a gasification reactor and a gas engine had an energy efficiency of 15–20% and large-scale (>5 MW) systems via an integrated gasification combined cycle had an electrical efficiency of 26–30%. Low system efficiencies and high costs incurred by collection, transport, and pretreatment are some of the major barriers to the economic feasibility of biochar production systems in China. Mobile systems or distributed biochar production systems serve as promising solutions to reduce the biomass cost by utilizing locally generated waste biomass and catering for the bioenergy and biochar demands of local rural communities. From an energy application perspective, biochar production systems can generate heat and electricity, and biochar can serve as an energy storage material in supercapacitors and rechargeable batteries systems and can be used in anaerobic digestion to enhance overall energy recovery. Biochar can be used to achieve carbon sequestration and remediation of soil, and odor control in livestock farms. Systems converting locally generated biomass into energy and biochar that are used by local villages wait to be tested to clarify the intricacies of their viability and large-scale environmental and energy impacts in rural China.

Keywords: Sustainable development goals; Green and sustainable energy; Waste management

1. Introduction

As one of the biggest biological sectors, the agriculture sector accounts for the highest biomass production and 21% of greenhouse gas (GHG) emissions (Duque-Acevedo, et al. 2020). Sustainable management of agricultural waste such as animal waste, plant waste, processing residue and rural household waste is receiving increasing attention due to its significant social, environmental, and economic implications. Improper management of agricultural waste such as landfill and open fire burning has led a variety of environmental problems such as air quality degradation and significant GHG emissions in addition to the potential loss of renewable sources (He, et al. 2019).

China has a rural population of over 600 million and is one of the largest agricultural countries around the world (Kakwani, et al. 2019). China had abundant biomass resources (e.g., crop residues and firewood) equivalent to 1.171 billion tonnes of standard coal (Yang, et al. 2017). It was estimated that 930.8 million tonnes of crop residues were produced in 2015 (Ji 2015) and the annual firewood production was about 210 million m^3 (Ren, et al. 2008). 280 million tonnes of firewood and 150 million tonnes of straw are used as the energy source for around 370 million rural households in China (Shan, et al. 2015). There has been significant interest to increase the share of biomass as the primary energy source in rural China while undertaking measures to increase the sustainability of biomass energy systems (Han and Wu 2018). Unfortunately, approximately 75% of biomass is discarded, directly burnt in the field or used by farmers for household cooking, which causes the problems of low-efficiency utilization (10%) and air pollution, as well as waste of valuable biomass resources (Huang, et al. 2019).

Sustainable bioenergy development and utilization have been a part of the national strategy in China. The Chinese Central government issued the Twelfth Five Plan (2011-2015) of Biomass Energy Development policy to guide and promote sustainable biomass use, with a particular emphasis on the development of biomass power generation, bio-fuel, biogas, and briquettes fuel (Shan, et al. 2016, Yang, et al. 2016). Sustainable utilization of agricultural residues and straw is an essential element of rural development in China's 12th and 13th Five-Year Plans. Relevant regulations have been formulated including subsidizing electricity generation from biomass, the provision of an added-value tax for products (e.g., electricity, heat, and bio-oil) derived from agricultural residues and other wastes, and strict banning of direct straw burning (Hong, et al. 2016, Yang, et al. 2016).

The benefits of bioenergy utilization are contingent upon the means of generation. Inappropriate utilization of biomass such as biomass burning in stoves has been a major cause of personal exposure to $PM_{2.5}$ (Lai, et al. 2019). In China, up to 40% of crop straw is burned in-field and contributes to 1.036 million tonnes of $PM_{2.5}$ emissions every year (Clare, et al. 2015, Zhang, et al. 2016). Approximately 0.67-0.93 million premature deaths were attributed to household air pollution associated with cooking and heating in rural China in 2010 (Chen, et al. 2018b).

Biomass use was expected to account for 6.5%-30% of China's 2100 primary energy production toward the Paris climate goals (Pan, et al. 2018). The CO_2 emission of rural energy consumption increased from 0.79 billion tonnes in 1979 to 1.98 billion tonnes in 2008 (Zhang, et al. 2014a). A recent survey of three Chinese provinces (Shanxi, Zhejiang, and Guizhou) showed that 37% of rural households used bioenergy for heating and cooking, accounting for 18% of their total energy use (Zhang, et al. 2014b). The bioenergy-related greenhouse gas (GHG) emissions were associated with economic development and inversely associated with energy efficiency improvement (Yang, et al. 2017). Meanwhile, the carbon footprints of bioenergy systems are contingent upon the technology options and system configurations (Clare, et al. 2015).

Rural China is facing several environmental challenges such as soil contamination and degradation associated with land-use transitions and widespread overuse of fertilizers and pesticides (Long and Qu 2018, Zhu, et al. 2018). Around 16.1% of the soil samples (19% for agricultural soils) in China are contaminated and 82.4% of the soil samples are contaminated with metals and metalloids (Zhao, et al. 2014). Soil contamination reduces eco-diversity and agricultural productivity, and pose a significant threat to China’s food security (Liu, et al. 2013). The government aims to recover 95% of the nation's contaminated land by 2030 according to the Soil Pollution Prevention and Control Action Plan (Hou and Li 2017). Additionally, 5.392 million km^2 land or 56.2% of the total land area experienced soil degradation, corresponding to an arable land area of around 1.3 million km^2, or 14% of the total land area (Zhao 2018). Soil erosion has spread a vast amount of organic matter and nutrients into water bodies, leading to the deterioration of water quality. A series of environmental protection measures (e.g., Grain for Green Project and planting of fast-growing woods on hills in southern China) have been adopted but they only partially fulfilled the target of recovering the soil erosion situation to the 1980s level by 2010 (Wang, et al. 2016).

Biochar production technologies (e.g., pyrolysis and gasification) serve as a promising solution to sustainably utilize biomass resources for both energy production and environmental mitigation for the rural areas of China while contributing to the fulfilment of climate change targets (You and Wang 2019). These technologies generate biochar as well as other products like synthesis gas (syngas – a mixture of carbon monoxide, hydrogen, and methane mainly) by gasification and bio-oil by pyrolysis. Biochar, syngas and bio-oil could be used as fuels for heat or electricity generation. Biochar can be used as a soil conditioner to address the problems of soil degradation and pollution due to its special physicochemical properties (e.g., porosity, high specific surface area, aromatic carbon structure, and alkalinity)

(Palansooriya, et al. 2019, Ye, et al. 2019, Ye, et al. 2017). It has the potential to increase soil fertility and carbon storage (and thus improved nutrients and water availability) and the mineralization, fixation and transformation of organic nitrogen, and facilitate aggregate formation (Panahi, et al. 2020, Tan, et al. 2017). Relevant policies have been developed in China to encourage the use of biochar-based fertilizers to reduce the over-dependence on chemical fertilizers (General Office of the Ministry of Agriculture 2017). The soil application of biochar has an additional benefit of carbon sequestration due to biochar recalcitrance in soil, reduced soil N_2O emission, and crop growth enhancement (Lehmann 2007), which might be vital considering that agriculture accounts for 11% of China's GHG emissions (Wang, et al. 2015). Moreover, it has been evidenced that biochar has the potential to serve a cost-effective green sorbent for various environmental mitigation applications such as CO2 capturing and contaminant removal (Dissanayake, et al. 2020, Wang, et al. 2019). It is feasible to achieve benefits of biochar production systems in multi-generation. The technologies are suitable for empowering remote rural areas using localized waste biomass (You, et al. 2017b), which will divert biomass utilization from in-field burning to higher-efficiency, less-emission generation.

Although there are no fixed principles on the practical implementation of biochar production systems in rural areas, the basic guideline is that the development needs to precisely match the economic, social, energy or environmental demands of the area for which a system will serve. This could be achieved by adjusting the relevant productivity of the products according to demands and is good for speeding up the uptake and implementation of relevant technologies (You, et al. 2018). This, however, is subject to a comprehensive evaluation of their interests with investors, policymakers, and rural households, which are closely associated with the economic, energy and environmental (3E) impacts of the systems. It is impossible to achieve optimal planning of biochar production without understanding the

3E impacts and their relationships with the geographical variations of energy and environmental demands. Here, we summarize the current development status and 3E impacts of biochar production systems and identify the critical influential factors of biochar system implementation in rural China.

2. Biochar production

2.1 Technologies

Torrefaction, pyrolysis, and gasification are three of the major production technologies that have been used for industrial applications. Torrefaction occurs between 200 and 300 °C in an inert atmosphere and primarily produces biochar that has a higher heating value and hydrophobicity than raw biomass and is suitable for higher quality syngas production in a subsequent gasification process (Cahyanti, et al. 2020). Hence, torrefaction systems have been commonly used to pre-treat biomass. Pyrolysis occurs between 300 and 900 °C in the absence of oxygen and has three major products: biochar, bio-oil, and syngas whose relative productivities depend on the temperature, residence time and heating rate of the process (Kumar, et al. 2020, Zhang, et al. 2019). Bio-oil and syngas can be used to generate heat and/or electricity or upgraded to value-added chemicals (e.g., transportation liquid fuel and hydrogen) (Hansen, et al. 2020, , You, et al. 2018). Compared to torrefaction and pyrolysis, gasification normally occurs at a higher temperature (>500 - 700 °C) and in the presence of limited oxygen (You, et al. 2017a, Cao, et al. 2020). Syngas is the primary product of gasification and the production of biochar is normally less than 20 wt.% of raw biomass. Advanced biochar production technologies are also receiving attention. For example, the decomposition and depolymerization of biomass can be carried out at a low temperature in a hydrothermal carbonization process, leading to the production of hydrochar (Antero, et al. 2020,).

2.2 System development in China

Bioenergy (electricity and heat) has been the dominant output of existing gasification-based systems in China while the biochar produced is still underutilized. Existing gasification systems range from small- and medium-scale (a few kW to 3 MW) consisting of a gasification reactor (fixed bed for systems less than 200 kW and bubbling fluidized beds or circulating fluidized beds for 200–3000 kW) and a gas engine with energy efficiency of 15–20% to large-scale (>5 MW) via an integrated gasification combined cycle with an electrical efficiency of 26–30% (Zhou, et al. 2012). A 1 MWe circulating fluidized-bed gasification plant was demonstrated in Fujian Province of China in 1998 that converted rice husk (150 tonnes d^{-1}) to electricity with an efficiency of 17% (Yin, et al. 2002). A 5.5 MWe integrated gasification combined cycle plant was demonstrated in Jiangsu Province in 2005 and converted rice husk, rice stalk, and wheat stalk to electricity with higher efficiency of 28–30% (Wu, et al. 2008). This system had a capital cost less than 1200$/kW which was 20% lower than the 1 MWe system, and an O&M cost of ~0.079$/kWh at a biomass price of 35.7$/tonne. Efforts are being focused on the technology upgrading of biomass gasification power generation to reduce capital investment and enhance electrical efficiency (Huang, et al. 2019).

Without considering the use of biochar and ash, the optimal capacity of agricultural straw gasification was estimated to be 5 MWe with an electricity cost of 0.056$/kWh (for CNY to USD exchange rate of 0.14 in 2019) and a net-present value (NPV) of $12.03 million at a feed-in tariff of 0.105$/kWh in China (Huang, et al. 2019). The Central government fully subsidized a 90 m^3 gasifier system in Guangxi Province that had capital and O&M costs of 16,744$ and 554$, and a daily gas supply of 40 m^3 (Zhang, et al. 2018b). The biochar was not used as a by-product, regardless of which, the centralized gasification system was found to have the best performance among various bioenergy generation options considered (centralized vs. residential and fermentation vs. gasification) (Zhang, et al. 2018b).

Pyrolysis and gasification can achieve multi-generation. Several pyrolysis-based biochar production plants with a capacity ranging from 365 tonnes/year to 48400 tonnes/year have been developed to utilize various types of waste biomass (e.g., cotton stalk, rice husk, forestry residue, wheat straw, and rape stalk) (Yang, et al. 2016). The biochar production capacity of the plants ranges from 80.3 to 11400 tonnes/year. These plants generate substantial syngas (1.8×10^4 - 1.58×10^7 m^3/year), wood tar (2.92 - 1920 tonnes/year), and wood vinegar (36.5 - 9520 tonnes/year) as well (Yang, et al. 2016).

One decentralized gasification system was built in suburban Beijing in 2007 to supply cooking gas to 387 households in a local village with biochar being a by-product for sale (Wang, et al. 2012). It utilized 144 tonnes/year of woody materials to generate 4.50×10^{-2} million m^3/year of cooking gas (LHV=14.7 MJ/m^3) and 27 tonnes/year of biochar. The system appeared to be hardly sustainable due to the high cost of raw material (increased from 39$/tonne (for CNY to USD exchange rate of 0.13 in 2007) in 2007 to 63$/tonne (for CNY to USD exchange rate of 0.15 in 2007) in 2011) and relatively low system efficiency. It is not clear if the biochar was used for soil amendment and contributed to the profitability accounting of the system.

3. Economic viability

The economic viability of biochar production systems can be evaluated using cost-benefit analysis where all cash flows associated with the development and operation of a system are examined over a certain period (e.g., system lifetime) and, in many cases, resolved to their equivalent “present” cash flow (i.e. so-called net-present worth analysis). Typical cost and benefit components for biochar productions systems include capital costs (e.g., system construction, land procurement, and interest payments), operation and maintenance (O&M) costs (e.g., staff salary and training, equipment maintenance cost, transport, biomass cost, and biochar application), sale of products (e.g., biochar, heat, electricity, etc.), carbon tax, financial subsidies, etc (You and Wang 2019).

3.1 Economic barriers

Low system efficiencies and high costs incurred by collection, transport, and pretreatment are some of the major barriers to the economic feasibility of biochar production systems in China (Wang, et al. 2012, Zhou, et al. 2012). Increasing energy efficiency is critical to enhancing the economic viability of gasification-based systems. Guangzhou Institute of Energy Conversion (GIEC) developed an integrated gasification combined cycle system consisting of a large-scale circulating fluidized bed, a low calorific gas engine, and a subsidiary exhaust heat utilization system (Wu, et al. 2008). The system has a maximum electrical efficiency of 30% and was economically viable (Wu, et al. 2008). The power generation cost was reported to be 0.0790$/kWh based on a biomass price of 35.7$/tonne and this cost could be varied significantly depending on the price of biomass, which ranged from 35.7$/tonne to 42.9$/tonne.

Biochar production systems in rural areas need to be supported by active participation of rural households, which might incur the cost of household compensation for biomass collection. A recent nation-wide survey (He, et al. 2018) showed that a compensation of approximately 0.95% – 1.62% of the average family annual income is needed to encourage households to actively participate in energy utilization of crop straw. An econometric analysis showed that a 1% increase in biomass collection time reduced bioenergy use by 0.8% in China, suggesting that the opportunity cost of biomass collection can affect practical operation of biochar production systems via the way of household participation (Zhang, et al.

2014b). To facilitate biomass collection, the concept of mobile pyrolysis systems has been proposed. The mobile systems incur a significant labor cost but have a reduced cost of raw material due to shorter biomass haul distances as compared to fixed systems (Chen, et al. 2018a). A recent study demonstrated the economic feasibility of portable systems that produced solid biofuels and biochar from forest residues (Phillips, et al. 2018).

Distributed biochar production systems serve as another option to reduce the biomass cost by utilizing locally generated waste biomass and catering for the bioenergy and biochar demands of local rural communities. Utilizing grass seed screenings and straw, a farm-scale gasification system in NE Washington State produced enough electricity for on-farm usage and quality biochar whose tillage application improved the yields by a factor of 2.88 for 6.3–11.8% of the production area annually (Phillips, et al. 2018). Utilizing chicken manure and wood waste in a ratio of 3:7, a gasification system in a hen layer farm produced syngas of quality comparable to that of gasification of pure wood waste, and the produced biochar was able to remove contaminants in water (Ng, et al. 2017). The profitability of the system increased from 41.5% to over 90% if either the biochar price or electricity tariff were doubled, or the woodchip price was halved. The concept of farm-scale biochar production systems suggests that it is vital to incorporate the design of biochar production into the rural planning of sustainable development.

3.2 Role of biochar

The potential of biochar valorization in improving the profitability of pyrolysis and gasification systems has been paid significant attention; this is accelerated by extensive findings on the benefits of the soil application of biochar in recent years. Biochar can diversify the income sources of biomass utilization systems in view of its energy and environmental impacts as shown in Figure 1. Figure 1 shows some potential technology routes (as detailed in the following sections) for biochar production as supported by relevant governmental policies. The governmental subsidies and the actual 'market' values of the different routes will define the income flow of a biochar production system. A recent study showed that biochar sale at a price of 14–112$/tonne (for CNY to USD exchange rate of 0.14 in 2019) reduced the cost of electricity by 2.5–20% and increased the NPV by $0.336-3.752 million for a 5 MWe gasification system (Huang, et al. 2019).

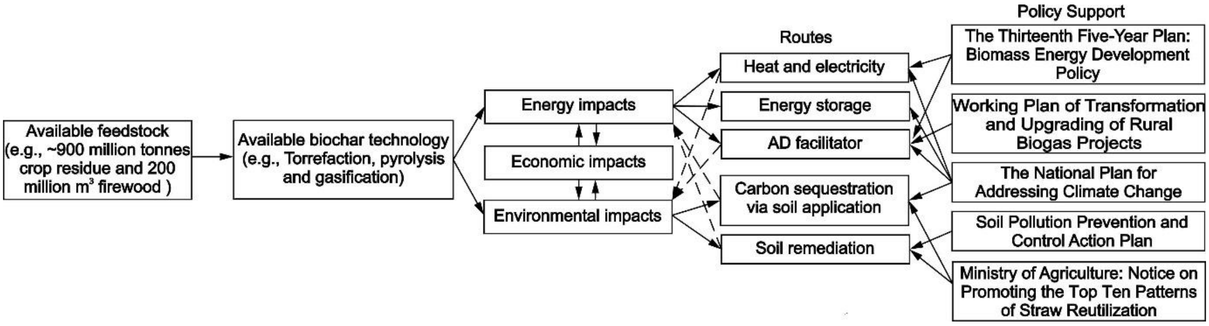

Figure 1. Routes of multi-purpose biochar production systems in relation to relevant policy support. The dash lines denote an indirect relationship.

A high economic value in biochar is needed to cover the cost of biomass collection and to ultimately promote sustainable biomass use, as the high opportunity cost of labour in biomass collection was found to adversely affect bioenergy use (Zhang, et al. 2014b). Clare, et al. (2015) compared the economic viability of biochar (8300 tonnes/year) and electricity (8400 MWh/year) production via straw pyrolysis, with that of briquettes (28000 tonnes/year) and electricity (26680 MWh/year) production via briquetting and gasification, respectively, in China. In the baseline scenario where the value of biochar was 110$/tonne, the biochar production system was not profitable with an NPV of −1.84$ million under a national electricity subsidy of 0.12$/kWh and a local straw-burning avoiding subsidy of 28$/tonne. The biochar value needed to be higher than 128$/tonne to break even the biochar production system. Without subsidies, the value of biochar needed to be at least 238$/tonne so that the biochar production system had the same NPV as that of the gasification system.

There is a compromise between the profitability of production and farmers' affordability if biochar is used by farmers for soil amendment. The current price of commercial biochar that has been widely used for in-field research in China is approximately 360$/tonne without considering the cost of biochar transportation (Qifa, et al. 2018). This was claimed to be too high to be affordable for farmers. In China, crop production activities are mostly carried out in the level of households where the use and purchase of fertilizers and pesticides account for a significant cost component (Zhang, et al. 2013). Hence, there is an indirect economic benefit for rural households from soil application of biochar by means of reduced use and purchase of fertilizers and pesticides. A recent study showed that biochar application in paddy soil led to an economic gain of 1.5×10^3\$/ha for rice and wheat rotation without considering the cost of biochar (Zhang, et al. 2013).

The pricing of biochar is associated with the economic benefit of farmers and the economic viability of biochar production systems. There exists an optimal biochar price that is not only essential for the economic viability of biochar production systems but also necessary for the sustainable operation of the systems that rely on the active participation of local rural households. This warrants more research about field-testing of application and quality control of production to accurately define the agronomic value of biochar. Existing studies (Liu, et al. 2012b, Qian, et al. 2014, Wang, et al. 2018b) exploring the agronomic impacts of biochar in China were often based on commercial biochar derived from the pyrolysis of wheat and maize straw, pig manure compost, peanut husk, and household biowaste by Sanli New Energy Company in Henan province. It is necessary to study the agronomic impact of biochar based on different types of biomass cross different areas as well as the different biochar production technologies.

4. Energy impacts

4.1 Energy status

China has replaced the United States as the world's leading energy consumer since 2009, accounting for 22.5% of the global energy consumption in 2014 (Musa, et al. 2018). The Chinese government has made great efforts to electrify remote districts and counties. However, inequality in energy consumption still exists and many inhabitants in remote rural areas still have no access to grid electricity (Shi 2019). In China, 71.7% of the overall power generation is made by thermal power, about 85% of which is contributed by coal power (Liu and Lv 2019). The Chinese government plans to reduce the over-dependence on fossil fuels and corresponding GHG emissions by increasing the use of renewable energy where bioenergy plays an essential element (Kang, et al. 2015). As a supplement to the national grid, decentralized electricity generation is a solution for remote rural and mountain areas. Power generation systems based on biomass technologies might be economically more feasible than those based on fossil fuels for remote rural or mountain areas because of the availability of rich lignocellulosic biomass sources (You, et al. 2017b). Biochar production systems with multi-generation can potentially adjust the energy structure of China and provide a promising strategy for green sustainable development.

4.2 Energy potential

This work will examine the energy potential of biochar with respect to the heat and electricity production from gasification (biochar as a by-product) or burning of biochar, its role as an energy storage material in supercapacitors and rechargeable batteries systems, and its role in enhancing energy recovery from anaerobic digestion (AD). All of these are consistent with China's National Plan for Addressing Climate Change (2013-20) aiming to increase the share of non-fossil fuel energy to 15% (Piovani 2017).

4.2.1 Heat and electricity

China's installed capacity of biomass power generation increased sharply from 1.4 GW in 2006 to 14.8 GW in 2017, which accounts for 12.2% of global capacity of biomass-powered plants (Gu, et al. 2018). Around 1000 biomass gasification installations are in operation throughout China, with different types and scales (Yang, et al. 2018). Data from the Renewable Energy Policy Network for the 21st Century, REN21 indicated that, during 2015, 822,000 jobs were generated in the solid biomass sector, globally, without counting several million generated in the traditional sector; in China there were 241,000 small- or medium-scale biomass gasification power generation systems (Islas, et al. 2019).

As mentioned earlier, the direct combustion of biomass for heat production has the limitations of smoke emission and low energy efficiency (Tsai, et al. 2012). Biochar serves as a high-energy-density solid fuel with lower H/C and O/C ratios and lower smoke emission upon thermochemical processing (Abdullah 2009). The carbon content of palm kernel shell biochar from a bubbling gasifier was 75 - 91% with a higher heating value (HHV) of around 28 MJ kg^{-1}, comparable to the heating values of bituminous coal (Fisher, et al. 2012). Using date leaves and lawn wastes as feedstock, the HHV of the biochar produced at 250, 350 and 450 ºC were 24, 23.64 and 23.08 MJ kg^{-1} (Waqas, et al. 2018). The energy density of biochar (~28 MJ kg^{-1}) produced at low temperature (330 ºC) was even higher than Collie coal (~26 MJ kg^{-1}) (Abdullah 2009). Due to their high heating values, biochar could be used as the feedback for gasification to produce extra gaseous fuel (Le and Kolaczkowski 2015, Pacioni, et al. 2016). Biochar co-firing technology can reduce the energy dependence on fossil fuel and increase fuel diversity for coal-fired thermal power systems. For example, biochar could be blended with Australia coal for pelletizing and combustion in a single pellet furnace, leading to easy ignition and long-lasting char combustion (Li, et al. 2018b).

4.2.2 Electrochemical energy storage

Electrical energy storage systems including supercapacitors and rechargeable batteries attract broad interests in the field of electronics, electric vehicles, and renewable energy storage. The former possesses high power density and cycle stability, while the latter have high energy density but low charge/discharge rate and cycle stability (Cheng, et al. 2017). Carbon electrode materials primarily decide the performance of electrochemical energy storage devices. Featured by high carbon content, carbon-oxygen groups, and electrical conductivity, and large specific surface area, biochar has great potential to serve as electrocatalysts and supercapacitors. The non-soil application of biochar will facilitate the valorization of biochar, improving the economics of biochar production systems.

Direct carbon fuel cells (DCFCs) received increasing attention due to their high electrical efficiency, size flexibility, and overall reliability (Giddey, et al. 2012). Wood biochar could achieve a higher power density than commercial activated carbon, even if the specific surface area of biochar was smaller than that of activated carbon (Alexander, et al. 2012). The conductive properties of biochar were positively related to its texture and anomeric O–C–O carbons and the heteroatoms such as oxygen, nitrogen, and sulfur (Shafeeyan, et al. 2010). Proper activation can improve the capacitance of biochar. When the carbon content of biochar increased from 86.8 to 93.7 wt%, the capacitance increased by a six-order magnitude (Gabhi, et al. 2017). By activation, biochar can be upgraded into carbon nanotubes, which provides a higher surface area and more microporous structures leading to the promoted performance. The increase of mesoporous structure was found to have negative effects on capacitance (Dehkhoda, et al. 2010). The chemical modification of biochar's surface properties could facilitate its supercapacitor application (Elmouwahidi, et al. 2012, Jiang, et al. 2013). Although the surface area decreased slightly after the activation in HNO_3 solution, the capacitance improved because of the increase in the coverage of surface oxygen groups (Jiang, et al. 2013). The performance of the activated biochar in supercapacitors was found to be better than that of commercial activated carbon or graphene. The total capacitance of the activated biochar electrodes was up to about 50 times higher than that of Vulcan electrodes prepared by the same technique, and was also competitive with much more expensive systems such as carbon nanotubes and graphene-based electrodes. The capacitive performance of the KOH activated biochar was found to be better than general bio-inspired activated carbons, ordered mesoporous carbons and commercial graphene (Jin, et al. 2013).

The supercapacitor electrodes, made from biochar had a potential of about 1.3 V and fast charging-discharging behavior with a gravimetric capacitance of about 14 F/g (Jiang, et al. 2013). Liu, et al. (2012a) synthesized a high-performance supercapacitor from biochar-derived carbon monolith from poplar wood followed by surface modification with nitric acid. It had a highly consistent structure and high porosity with specific capacitance as high as 234 F/g. The maximum current density of algal biochar anode was about 4.1 times higher than graphite plate anode in a bio-electrochemical system because the algal biochar electrode could effectively utilize both indirect and direct electron transfer pathways for current production, and had stronger electrochemical response and better adsorption of redox mediators (Wang, et al. 2018c).

Biochar has good properties to support microbial redox transformation by accepting and/or donating electrons. Electron storage capacity (ESC) is an important property that determines the capacity of biochar to mediate redox processes in natural and engineered systems. Pore diffusion within biochar particles was rate-limiting and controlled the timescale for redox equilibrium. Redox-facile functional groups in biochar were distributed over a broad range of potentials. The ESC measured using dithionite indicated that approximately 22% of the biochar's reversible ESC was accessible to *G. metallireducens* (Xin, et al. 2019).

4.2.3 Integration with anaerobic digestion

Biochar production systems can be integrated with anaerobic digestion (AD) systems to improve energy recovery from AD (Chen, et al. 2012), leading to an indirect increase in the economic value of biochar. AD is being widely used in rural China and the Central government has initiated the 'Working Plan of Transformation and Upgrading of Rural Biogas Projects' to encourage the technology, management and development of large-scale biogas projects for disposing of 1.5 million tonnes of crop straw and 8 million tonnes livestock dung in rural areas (Chen and Liu 2017).

The hybrid design consisting of biochar production and AD will favour the effective utilization of waste biomass. AD, especially the high-solid or dry process, is easily inhibited by the accumulation of ammonia or volatile fatty acids (VFAs), which need to be removed by buffering agents (Li, et al. 2018a, Li, et al. 2017a). Biochar serves as an ideal buffer agent for its rich porosity and alkali and alkaline earth metallic (AAEM) species. The AAEM species contained in the gasification biochar could be released in the form of cations which could react with organic acids or CO_2, thus, keeping the pH stable (You, et al. 2017a). The large specific surface area and porous structure of biochar favour the colonization of syntrophic acetogenic bacteria and methanogenic archaea, which together with the increased reaction rate facilitated the total organic carbon removal by AD.

Biochar can improve the buffering capacity of AD systems by accelerating the transformation of macromolecular substances to dissolved substrates and reducing the contents of soluble salts, total ammonia nitrogen, and free ammonia (Pan, et al. 2019). Biochar promoted the VFA production process and altered the fermentative type from that of acetate type to butyrate type, which seemed to have higher efficiency for H_2 production. Biochar addition was found to shorten the lag time by circa 18–62% and increase the maximum H_2 production rate by circa 18–110%. The biochar produced at higher temperatures enhances H_2 production more dramatically than those derived at low temperatures. The pH buffering capacity of biochar was critical to the promotion of fermentative H_2 production by mitigating the pH decrease caused by VFAs accumulation (Wang, et al. 2018a). Carbons can serve as a habitation for microbial immobilization, and a provision for bioelectrical connections among cells, and provide some essential elements for anaerobes, thus, can change the structure of microbial community (Zhang, et al. 2018a). The gasification of digested residue can serve as a second stage after AD and produce syngas, which shows higher overall energy recovery efficiency than the sole process of AD or gasification (Yao, et al. 2017, Zhang, et al. 2018a).

5. Environmental impacts

5.1 Climate change

Recalcitrant carbon in biochar mainly in forms of graphite could persist in the soil for hundreds of years. There have been some preliminary studies evaluating the global warming potential of biochar production systems in China. For example, Yang, et al. (2016) analyzed the GHG emission intensity of one of the pyrolysis plants in Hubei that consisted of three major components, i.e. a drying and molding system, a pyrolysis carbonization system (two heating furnaces and five retorts with a diameter of 1.6 - 2.2 m each), and a separation and purification system (separating tower, cooling tower, and filter tower). It was shown that the emission intensity was 15.5 or -61.1 g $CO_{2\text{-eq}}$/MJ if biochar was burned for energy or returned to the field for soil amendment. The latter led to a nation-wide $CO_{2\text{-eq}}$ reduction of 9.43×10^5 tonnes, if 50% of biomass was used for biochar production. The global warming potential of corn straw-based gasification system for supplying the cooking gas to rural households was estimated to be 66.97 g $CO_{2\text{-eq}}$/MJ without considering the impact of biochar utilization (Yang and Chen 2014). The decentralized gasification system in Beijing consumed 2.93 J energy to generate one joule of biomass gas with a GHG emission of 1.17×10^{-4} g $CO_{2\text{-eq}}$ (Wang, et al. 2012). However, there is still lacking a systematic differentiation of the roles of biochar production routes on decarbonizing the rural development in China.

Biochar addition can mitigate the direct emissions of GHG (e.g., CH_4 and N_2O) via soil management. N_2O-N emission per metric was reduced from 0.17 ± 0.02 kg N_2O-N to 0.10 ± 0.02 and 0.07 ± 0.03 kg N_2O-N when biochar was applied to rice soil at 20 tonnes/ha and 40 tonnes/ha, respectively, in China (Liu, et al. 2012b). Compared with the control scenario without biochar addition, biochar amendment reduced CH_4 flux and gross GHG emission by 26.18% and 26.14%, respectively due to enhanced biodiversity, methanotrophic microbes, soil pH and soil aeration (Qin, et al. 2016). Rice straw biochar derived by 500 °C pyrolysis reduced CO_2 and N_2O emission by 4−40% and 62−98%, compared to the untreated soils (Li, et al. 2013). Biochar produced at a higher temperature (500 °C) has a greater effect in reducing soil GHG emission compared to that at a lower temperature (300 °C) (Li, et al. 2013).

Biochar can lead to indirect carbon abatement by enhancing soil quality and thus crop yields. The yield of rice and wheat production in a rice paddy in South-eastern China was enhanced by 9-13% and 17-36% respectively after a single biochar application (20 tonnes/ha and 200$/tonne) over six years (Wang, et al. 2018b). Biochar addition into a rice paddy in the Tai Lake Plain increased rice productivity, soil pH, soil organic carbon, total nitrogen, methane emission but decreased soil bulk density and nitrous oxide emission (Zhang, et al. 2012). Biochar addition also reduced the overall global warming potential by 7.1% to 18.7% in the second growth cycle. Qian, et al. (2014) compared the agronomic effects of four organic/inorganic compound fertilizers of biochar with conventional chemical fertilizers in a rice paddy application and found that biochar-based fertilizers improved N use efficiency (and thus reduced N input) and reduced GHG emissions (35-44%) during rice production (Qian, et al. 2014). Biochar addition (8 tonnes/ha) increased the mean concentration of dissolved organic carbon from 83.99 mg/kg to 144.27 mg/kg in maize rotation system in Loess Plateau of China under the same fertilizer application (Zhang, et al. 2017). Soil amendment of wheat straw biochar in a rice paddy in Tai Lake plain of Yixing, Jiangsu Province directly decreased soil CO_2 emission by 16–24% and the seasonal total N_2O emission by 30.7-48.6 % at 20 and 40 tonnes/ha of biochar application. It also increased the rice yield by 25–26 % and enhanced ecosystem CO_2 sequestration by 47–55%. Overall, 20 and 40 tonnes ha^{-1} wheat straw biochar led to a net decrease in GHG balance by 53.9–62.8% and GHG intensity by 14.3–28.6% (Zhang, et al. 2015a).

5.2 Soil remediation

Biochar addition can mitigate the problems of soil degradation and contamination, which will indirectly benefit the extensive reforestation programs as supported by the National Plant for Addressing Climate Change (2013-20) in China (Piovani 2017). Biochar can sorb some liable contaminants in soils, such as toxic metals or metalloids and pesticides, to reduce their mobility, bio-accessibility, and toxicity (Zhang and Tsang 2019). Soil application of rice straw biochar (500 °C) reduced annual soil runoff by 19–28% and annual sediment yield by 11%, as well as substantial nitrogen (N) and phosphorus (P) losses in the Danjiangkou Reservoir area at Hubei province (Li, et al. 2017b). Ten percent of sewage sludge biochar addition into the soil reduced the daily intake of potentially toxic elements (As, Cd, Co, Cu, Mn, Pb, and Zn) via rice consumption by 22-68% (Khan, et al. 2014). The addition reduced the concentrations of AsIII, dimethylarsinic acid, and AsV in rice by 72%, 74%, and 62%, respectively. This led to a 66% reduction in the incremental lifetime cancer value for iAs (AsIII + AsV) associated with rice consumption, which has been a major driver of cancer in China's "Cancer Villages". Bean stalk and rice straw biochar reduced Cd concentrations in iron plaque, roots, shoots and grain of rice plants by 35–81 %, 30–75%, 43–79% and 26–71%, respectively in Zhuzhou, Hunan province (Zheng, et al. 2015). The biochar addition also reduced the zinc concentrations in roots and shoots by 25.0–44.1% and 19.9–44.2 %, respectively. In a three-year (2010-2012) field study in a contaminated rice paddy in Jingtang village, Yixing, Jiangsu Province (31◦24'N and 119◦41'E) by Bian, et al. (2014), a single soil amendment by 20 and 40 tonnes/ha wheat straw biochar significantly increased the rice yields by 16.6% and 18.3%; Cd contents in the rice grain decreased significantly over the 3-year amendment. Similarly, in a 3-year field study performed by Sui, et al. (2018) in a field near adjacent villages in mining areas in Jiyuan, Henan Province, the application of wheat straw biochar decreased the Cd and Pb bioavailability to wheat (*Triticum aestivum L.*), but significantly increased the grain yield by 5-8% and 10-14% in year 3 for 20 and 40 tonnes/ha biochar, respectively; it also reduced the grain Cd content by 6~16% for 20 tonnes/ha biochar application in year 1.

5.3 Odor control

A considerable amount of odor could be emitted from livestock farms in the rural areas. Application of biochars to remove the odor of Chinese livestock farms has never been reported. Biochar could be a practical treatment to control emissions from stored manure in as shown in Table 1. Some researches for removing odor from livestock farms with biochars have been reported (Dougherty, et al. 2017, Hwang, et al. 2018, Maurer, et al. 2017) and biochar could potentially be applied in Chinese livestock farms. For example, various biochars were prepared by pyrolyzing poultry litter, swine manure, oak, and coconut shell to remove 15 odorous volatile organic compounds produced from swine manure where was obtained from a 5000-head finishing farm in North Carolina (Hwang, et al. 2018). Among various biochar, oak biochar pyrolyzed at 500 ^oC showed higher sorption capacity for the adsorption of dimethyl disulfide and dimethyl trisulfide (major malodor compounds in swine manure) in lab scale (Hwang, et al. 2018). A pilot-scale experiment was carried out to control malodor, H_2S, NH_3, GHG from swine production in Midwestern U.S. swine barn (Maurer, et al. 2017). Biochar was floated on top of swine manure over a month to mitigate the emission of NH_3, H_2S, DMDS, DMTS, fatty acids, cresol, indole, and GHGs produced from swine manure. As a result, a thin layer of biochar as manure additive was effective to diminish malodor and some of VOCs from swine product even though there was a significant increase of CH_4. It is worth noting that biochar can be used for urban/industrial wastewaters treatment as a very important and promising development for biochar application in addition to odor removal. This application of biochar is excluded, however, as this work focuses on the use of biochar for rural development.

Table 1. Removal of malodorous gases from livestock farms by biochars

Feedstock	Pyrolysis temperature	Quantity	Contaminant	Input concentration	Efficiency	References
Oak	500 ^oC	10.0 g	DMDS[a]	18.9 ng/L	448 ng/g	Hwang, et al. (2018)
Oak	500 ^oC	10.0 g	DMTS[b]	4.8 ng/L	107 ng/g	Hwang, et al. (2018)
Pine	495 – 505 ^oC	4.56 kg/m^2	NH_3	<1000 mg/hm^2	0.84 mg/g	Maurer, et al. (2017)
Cattle manure	550 ^oC	10% w/w	VOCs[c]	-	33.1% - 100%	Kyriaki, et al. (2020)
Beechwood	-	2%-4% w/w	NH_3	-	14% - 15%	Kalus, et al. (2020)
Cornstalk, bamboo, wood, layer manure and coir	400 – 700 ^oC	10% w/w	NH_3	-	9.2% - 24.8%	Chen, et al. (2017)
Douglas fir bark and center wood	600 ^oC	-	NH_3	-	72% - 80%	Dougherty, et al. (2017)
Spruce	650 ^oC	-	H_2S	~39 $g\ m^{-3}\ h^{-1}$	~70%	Das, et al.

(2019)

[a]Dimethyl disulfide, [b]Dimethyl trisulfide, [c]Volatile organic compounds, [d]Volatile fatty acid

5.4 Influential factors

The environmental impacts or footprints of a biochar production system is associated with the types of feedstocks and processes. The biomass type is one of the most important factors affecting the properties of produced biochar. For instance, biochar produced from crop straw generally exhibits a higher yield, biochar pH, and ash content than the wood-based ones (Wang, et al. 2013). For the biochar production systems in rural China, the feedstock is mostly from agricultural residue, firewood, forestry residue, and organic waste (such as manure, municipal domestic waste). Specifically, more than 50% of the feedstock is derived from rice, wheat, corn, beans, cotton and sugarcane and 22% from animal excreta or manure (Owens 2007). The former types of feedstocks generally have a high lignin content, and the derived biochar tends to have more acid functional groups and lower pH (Huang, et al. 2018). Sun et al. examined the yield and physicochemical characteristics of biochar produced from 60 types of biomass waste in six source categories including agricultural residues, woody pruning waste, aquatic plant material, nutshells and fruit peels, livestock manure and residual sludge in China (Sun, et al. 2017). They found that the yields of biochar were positively correlated with the contents of cellulose, lignin and lignin/cellulose in feedstocks, and the fixed carbon content of biochar was positively and negatively associated with the lignin/cellulose contents and ash content in feedstocks, respectively. They also showed that the property differences among the derived biochar were smaller within an individual biomass category than across different biomass categories.

The suitability of biochar for soil application is also affected by the contaminant contents of biomass that the biochar has been developed from. The contaminant contents in some feedstocks may not be ignorable. For example, various toxic metals (e.g., As, Cd, and Pb) have been detected in the agricultural residues in some heavy metal-contaminated areas. Approximately 13.86% of grain production was affected by the heavy metal pollution in farmland soil due to mining and smelting activities, industry, irrigation by sewage, urban development, and fertilizer application (Zhang, et al. 2015b). In the Dabaoshan mining zone, Guangdong province, food crop plantation is not suitable anymore, and some energy crops or fiber crops are planted instead (Zhuang, et al. 2009). This suggests that biochar derived from some of these agricultural residues may contain considerable contaminants originated from the soil.

The agronomic effects of biochar are determined by its physicochemical properties which are closely associated with the conditions of thermochemical processes (You, et al. 2018). For the biochar prepared from three major crop straws (rice, wheat, and corn straw) of China, the carbon content increased while the polar acidic functional groups decreased as the increased pyrolysis temperature (Wei, et al. 2017). The hemicellulose and cellulose components likely decomposed at about 300 ^{o}C and more condensed and ordered aromatic carbon structures were formed in the biochar at a higher pyrolysis temperature. Biochar produced at a higher temperature is often characterized by a larger surface area and aromatic carbon content as well as higher recalcitrance. The biochar prepared at a low temperature, less than 300 ^{o}C, often retains some polar function groups, such as hydroxyl, carboxyl carbonyl, etc, which may have positive effects on the soil quality and growth of plants in calcareous soils, and may increase the sorption capacity of biochar for ions in soil solution (Naeem, et al. 2017). On the other hand, to amend an acid soil or sequestrate carbon for a long term, the biochar prepared under a higher temperature may be more favourable.

The cation exchange capacity (CEC) of the fast-pyrolytic biochar from corn stover is about double of the gasification biochar and the CEC values often agree with the ratios of the oxygen atoms to the carbon atoms in the biochar, that is, a higher O:C ratio was consistent with the presence of more hydroxyl, carboxylate, and carbonyl groups in fast-pyrolytic biochar (Lee, et al. 2010). Therefore, the fast-pyrolytic biochar would be suitable for improving the soil properties such as CEC, and can be used as a carbon sequestration agent. Biochar obtained from manures have a high content of ash because they contain high levels of inorganic compounds, while wood and grass biochar have a low nutrient content, are carbon-rich, and have a higher rate of CO_2 adsorption (Liu, et al. 2018). The cotton stalk biochar had the highest fixed carbon content and lowest H/C ratio, and thus can be used as a solid biofuel.

The optimal biochar production conditions regarding it effects on soil remediation, carbon sequestration, and crop growth promotion are feedstock-, soil-, and crop-specific and thus need to be defined based on a comprehensive database accumulated by extensive, systematic, and standard in-field experiments. Some contaminants (e.g., polycyclic aromatic hydrocarbons (PAH) and dioxins) might be formed during the pyrolysis and gasification processes, which adds an extra layer of uncertainty into the evaluation of the environmental impacts of biochar (Oleszczuk, et al. 2013).

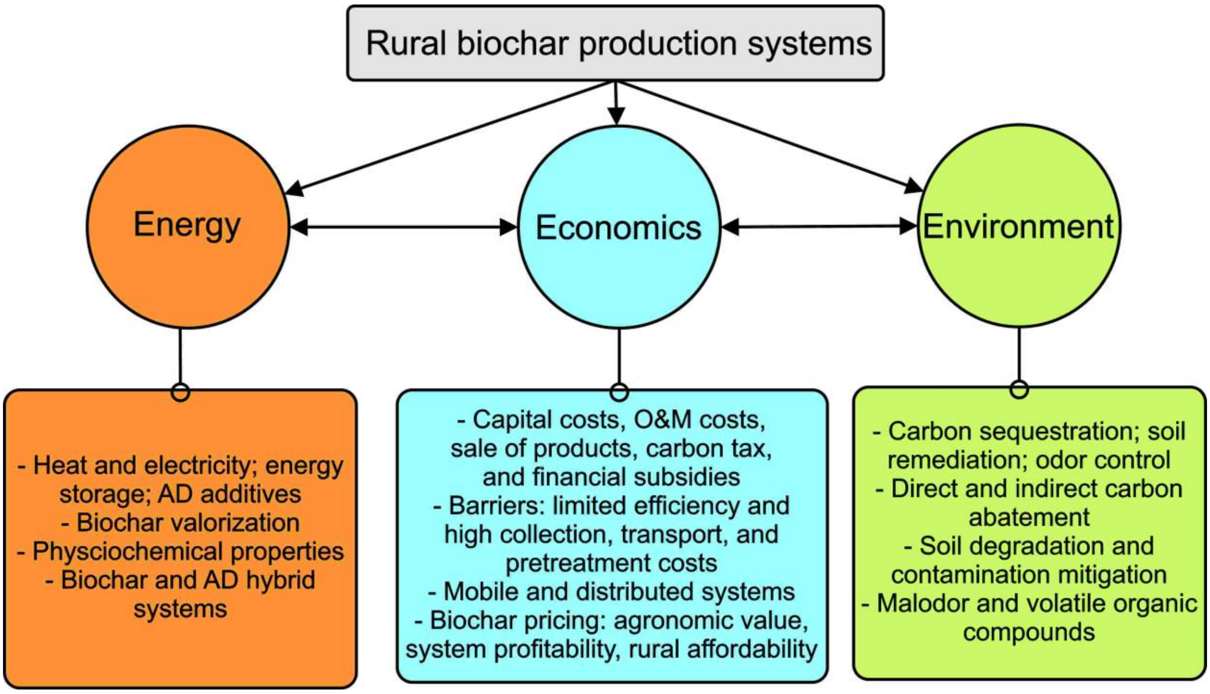

Figure 2. A summary of the economic, energy and environmental aspects of biochar productions systems

In summary, as shown in Figure 2, the economic, energy and environmental aspects are correlated with each other, affecting the practical implementation of biochar production systems in rural areas. Low system efficiencies and high collection, transport, and pretreatment costs may actually make a system economically infeasible. Mobile or distributed biochar production systems could be used to reduce the costs related to the collection and transport of biomass, but may be subjected to low efficiencies. Product sale, carbon tax, and financial subsidies are potential income sources of biochar development. The price of biochar would be resulted from a balance among the agronomic value of biochar, system profitability and affordability of rural households. From an energy application perspective, biochar production systems can generate heat and electricity, and biochar can serve as an energy storage material or be used in AD to develop hybrid systems with higher overall energy recovery. For the latter, the physicochemical properties of biochar play a central role and more research is needed to enhance the technical feasibility and achieve optimal performance. Biochar can be used to achieve carbon sequestration and remediation of soil or odor control in livestock farms.

6. Conclusions

As being promoted by a variety of governmental policies, biomass utilization is deemed to play an important role in decarbonizing China’s energy sector and achieving sustainable energy consumption in rural areas. However, relevant system development is biased toward energy production. Despite the increasing findings of the positive environmental effects of biochar, the concept of biochar production system has far from being incorporated into the rural development with insufficient attention to the multi-generation potential of biochar production systems. Distributed systems converting locally generated biomass to energy and biochar that are used by local villages await to be tested. The economic viability of biochar production systems is subject to further improvement in system energy efficiency and biochar valorization. The latter needs to account for the potential impact of biochar sale on the income of rural residents. The energy potential of biochar production systems is beyond the supply of heat and electricity when biochar is used for electrochemical energy storage and enhancing biogas production in hybrid designs. Environmental evidence has been accumulated to support the soil application of biochar, but there is a lack of information about the relationship between biochar production system design and intended environmental impacts since most of the in-field studies have been based on commercial biochar.

Acknowledgement

This research was supported by the Hydrogen Energy Innovation Technology Development Program of the National Research Foundation of Korea (NRF) funded by the Korean government (Ministry of Science and ICT (MSIT)) (No. NRF-2019M3E6A1064197) and the Scottish Funding Council Global Challenges Research Fund (SFC/AN/14/2019).

References

Abdullah, H.W., Hongwei (2009). 1. Properties and Grindability of Biochars Produced from the Pyrolysis of Mallee Wood under Slow-Heating Conditions *Energy & Fuels* 23, 4174-4181.

Alexander, B., Mitchell, R. and Gür, T. (2012). Experimental and modeling study of biomass conversion in a solid carbon fuel cell. *Journal of the Electrochemical Society* 159, B347-B354.

Antero, R. V. P., Alves, A. C. F., de Oliveira, S. B., Ojala, S. A., & Brum, S. S. (2020). Challenges and alternatives for the adequacy of hydrothermal carbonization of lignocellulosic biomass in cleaner production systems: A review. *Journal of Cleaner Production*, 252, 119899.

Bian, R., Joseph, S., Cui, L., Pan, G., Li, L., Liu, X., Zhang, A., Rutlidge, H., Wong, S. and Chia, C. (2014). A three-year experiment confirms continuous immobilization of cadmium and lead in contaminated paddy field with biochar amendment. *Journal of Hazardous Materials* 272, 121-128.

Cao, L., Iris, K. M., Xiong, X., Tsang, D. C., Zhang, S., Clark, J. H., ... & Ok, Y. S. (2020). Biorenewable hydrogen production through biomass gasification: A review and future prospects. *Environmental Research*, 109547.

Cahyanti, M. N., Doddapaneni, T. R. K. C., & Kikas, T. (2020). Biomass torrefaction: An overview on process parameters, economic and environmental aspects and recent advancements. *Bioresource Technology*, 301, 122737.

Chen, L., Zhao, L., Ren, C. and Wang, F. (2012). The progress and prospects of rural biogas production in China. *Energy Policy* 51, 58-63.

Chen, Q. and Liu, T. (2017). Biogas system in rural China: upgrading from decentralized to centralized? *Renewable and Sustainable Energy Reviews* 78, 933-944.

Chen, W., Liao, X., Wu, Y., Liang, J. B., Mi, J., Huang, J., ... & Wang, Y. (2017). Effects of different types of biochar on methane and ammonia mitigation during layer manure composting. Waste Management, 61, 506-515.

Chen, X., Zhang, H. and Xiao, R. (2018a). Mobile autothermal pyrolysis system for local biomass conversion: process simulation and techno-economic analysis. *Energy & Fuels* 32, 4178-4188.

Chen, Y., Shen, H., Smith, K.R., Guan, D., Chen, Y., Shen, G., Liu, J., Cheng, H., Zeng, E.Y. and Tao, S. (2018b). Estimating household air pollution exposures and health impacts from space heating in rural China. *Environment International* 119, 117-124.

Cheng, B.-H., Zeng, R.J. and Jiang, H. (2017). Recent developments of post-modification of biochar for electrochemical energy storage. *Bioresource Technology* 246, 224-233.

Clare, A., Shackley, S., Joseph, S., Hammond, J., Pan, G. and Bloom, A. (2015). Competing uses for China's straw: the economic and carbon abatement potential of biochar. *Gcb Bioenergy* 7, 1272-1282.

Das, J., Rene, E. R., Dupont, C., Dufourny, A., Blin, J., & van Hullebusch, E. D. (2019). Performance of a compost and biochar packed biofilter for gas-phase hydrogen sulfide removal. *Bioresource Technology*, 273, 581-591.

Dehkhoda, A.M., West, A.H. and Ellis, N. (2010). Biochar based solid acid catalyst for biodiesel production. *Applied Catalysis A: General* 382, 197-204.

Dissanayake, P. D., You, S., Igalavithana, A. D., Xia, Y., Bhatnagar, A., Gupta, S., ... & Ok, Y. S. (2020). Biochar-based adsorbents for carbon dioxide capture: A critical review. *Renewable and Sustainable Energy Reviews*, 119, 109582.

Dougherty, B., Gray, M., Johnson, M.G. and Kleber, M. (2017). Can biochar covers reduce emissions from manure lagoons while capturing nutrients? *Journal of environmental quality* 46, 659-666.

Duque-Acevedo, M., Belmonte-Ureña, L. J., Cortés-García, F. J., & Camacho-Ferre, F. (2020). Agricultural waste: Review of the evolution, approaches and perspectives on alternative uses. *Global Ecology and Conservation*, 22, e00902.

Elmouwahidi, A., Zapata-Benabithe, Z., Carrasco-Marín, F. and Moreno-Castilla, C. (2012). Activated carbons from KOH-activation of argan (Argania spinosa) seed shells as supercapacitor electrodes. *Bioresource Technology* 111, 185-190.

Fisher, E., Dupont, C., Darvell, L., Commandré, J.-M., Saddawi, A., Jones, J., Grateau, M., Nocquet, T. and Salvador, S. (2012). Combustion and gasification characteristics of chars from raw and torrefied biomass. *Bioresource Technology* 119, 157-165.

Gabhi, R.S., Kirk, D.W. and Jia, C.Q. (2017). Preliminary investigation of electrical conductivity of monolithic biochar. *Carbon* 116, 435-442.

General Office of the Ministry of Agriculture (2017). General Office of the Ministry of Agriculture's notice on promoting the top ten patterns of straw reutilization.

Giddey, S., Badwal, S., Kulkarni, A. and Munnings, C. (2012). A comprehensive review of direct carbon fuel cell technology. *Progress in Energy and Combustion Science* 38, 360-399.

Gu, H., Tang, Y., Yao, J. and Chen, F. (2018). Study on biomass gasification under various operating conditions. *Journal of the Energy Institute*.

Han, H. and Wu, S. (2018). Rural residential energy transition and energy consumption intensity in China. *Energy Economics* 74, 523-534.

Hansen, S., Mirkouei, A., & Diaz, L. A. (2020). A comprehensive state-of-technology review for upgrading bio-oil to renewable or blended hydrocarbon fuels. *Renewable and Sustainable Energy Reviews*, 118, 109548.

He, K., Zhang, J. and Zeng, Y. (2018). Rural households' willingness to accept compensation for energy utilization of crop straw in China. *Energy* 165, 562-571.

He, K., Zhang, J., & Zeng, Y. (2019). Knowledge domain and emerging trends of agricultural waste management in the field of social science: A scientometric review. *Science of the Total Environment*, 670, 236-244.

Hong, J., Ren, L., Hong, J. and Xu, C. (2016). Environmental impact assessment of corn straw utilization in China. *Journal of Cleaner Production* 112, 1700-1708.

Hou, D. and Li, F. (2017). Complexities surrounding China's soil action plan. *Land Degradation & Development* 28, 2315-2320.

Huang, Y., Li, F., Meng, J. and Chen, W. (2018). Lignin content of agro-forestry biomass negatively affects the resultant biochar pH. *BioResources* 13, 5153-5163.

Huang, Y., Zhao, Y.-j., Hao, Y.-h., Wei, G.-q., Feng, J., Li, W.-y., Yi, Q., Mohamed, U., Pourkashanian, M. and Nimmo, W. (2019). A feasibility analysis of distributed power plants from agricultural residues resources gasification in rural China. *Biomass and Bioenergy* 121, 1-12.

Hwang, O., Lee, S.-R., Cho, S., Ro, K.S., Spiehs, M., Woodbury, B., Silva, P.J., Han, D.-W., Choi, H. and Kim, K.-Y. (2018). Efficacy of different biochars in removing odorous volatile organic compounds (VOCs) emitted from swine manure. *ACS Sustainable Chemistry & Engineering* 6, 14239-14247.

Islas, J., Manzini, F., Masera, O. and Vargas, V. (2019). Solid Biomass to Heat and Power *The Role of Bioenergy in the Bioeconomy*, 145-177): Elsevier.

Ji, L.-Q. (2015). An assessment of agricultural residue resources for liquid biofuel production in China. *Renewable and Sustainable Energy Reviews* 44, 561-575.

Jiang, J., Zhang, L., Wang, X., Holm, N., Rajagopalan, K., Chen, F. and Ma, S. (2013). Highly ordered macroporous woody biochar with ultra-high carbon content as supercapacitor electrodes. *Electrochimica Acta* 113, 481-489.

Jin, H., Wang, X., Gu, Z. and Polin, J. (2013). Carbon materials from high ash biochar for supercapacitor and improvement of capacitance with HNO3 surface oxidation. *Journal of Power Sources* 236, 285-292.

Kaikiti, K., Stylianou, M., & Agapiou, A. (2020). Use of biochar for the sorption of volatile organic compounds (VOCs) emitted from cattle manure. *Environmental Science and Pollution Research*, 1-9.

Kakwani, N., Li, S., Wang, X. and Zhu, M. (2019). Evaluating the effectiveness of the rural minimum living standard guarantee (Dibao) program in China. *China Economic Review* 53, 1-14.

Kalus, K., Konkol, D., Korczyński, M., Koziel, J. A., & Opaliński, S. (2020). Effect of Biochar Diet Supplementation on Chicken Broilers Performance, NH3 and Odor Emissions and Meat Consumer Acceptance. *Animals*, 10(9), 1539.

Kang, S., Selosse, S. and Maïzi, N. (2015). Strategy of bioenergy development in the largest energy consumers of Asia (China, India, Japan and South Korea). *Energy Strategy Reviews* 8, 56-65.

Khan, S., Reid, B.J., Li, G. and Zhu, Y.-G. (2014). Application of biochar to soil reduces cancer risk via rice consumption: a case study in Miaoqian village, Longyan, China. *Environment International* 68, 154-161.

Kumar, R., Strezov, V., Weldekidan, H., He, J., Singh, S., Kan, T., & Dastjerdi, B. (2020). Lignocellulose biomass pyrolysis for bio-oil production: A review of biomass pre-treatment methods for production of drop-in fuels. *Renewable and Sustainable Energy Reviews*, 123, 109763.

Lai, A.M., Carter, E., Shan, M., Ni, K., Clark, S., Ezzati, M., Wiedinmyer, C., Yang, X., Baumgartner, J. and Schauer, J.J. (2019). Chemical composition and source apportionment of ambient, household, and personal exposures to PM2. 5 in communities using biomass stoves in rural China. *Science of The Total Environment* 646, 309-319.

Le, C. and Kolaczkowski, S. (2015). Steam gasification of a refuse derived char: reactivity and kinetics. *Chemical Engineering Research and Design* 102, 389-398.

Lee, J.W., Kidder, M., Evans, B.R., Paik, S., Buchanan Iii, A., Garten, C.T. and Brown, R.C. (2010). Characterization of biochars produced from cornstovers for soil amendment. *Environmental Science & Technology* 44, 7970-7974.

Lehmann, J. (2007). A handful of carbon. *Nature* 447, 143.

Li, F., Cao, X., Zhao, L., Yang, F., Wang, J. and Wang, S. (2013). Short-term effects of raw rice straw and its derived biochar on greenhouse gas emission in five typical soils in China. *Soil Science and Plant Nutrition* 59, 800-811.

Li, W., Loh, K.-C., Zhang, J., Tong, Y.W. and Dai, Y. (2018a). Two-stage anaerobic digestion of food waste and horticultural waste in high-solid system. *Applied Energy* 209, 400-408.

Li, W., Lu, C., An, G. and Chang, S. (2017a). Comparison of alkali-buffering effects and co-digestion on high-solid anaerobic digestion of horticultural waste. *Energy & Fuels* 31, 10990-10997.

Li, Y.-H., Lin, H.-T., Xiao, K.-L. and Lasek, J. (2018b). Combustion behavior of coal pellets blended with Miscanthus biochar. *Energy* 163, 180-190.

Li, Z.-g., Gu, C.-m., Zhang, R.-h., Ibrahim, M., Zhang, G.-s., Wang, L., Zhang, R.-q., Chen, F. and Liu, Y. (2017b). The benefic effect induced by biochar on soil erosion and nutrient loss of slopping land under natural rainfall conditions in central China. *Agricultural Water Management* 185, 145-150.

Liu, F. and Lv, T. (2019). Assessment of geographical distribution of photovoltaic generation in China for a low carbon electricity transition. *Journal of Cleaner Production* 212, 655-665.

Liu, M.-C., Kong, L.-B., Zhang, P., Luo, Y.-C. and Kang, L. (2012a). Porous wood carbon monolith for high-performance supercapacitors. *Electrochimica Acta* 60, 443-448.

Liu, X.-y., Qu, J.-j., Li, L.-q., Zhang, A.-f., Jufeng, Z., Zheng, J.-w. and Pan, G.-x. (2012b). Can biochar amendment be an ecological engineering technology to depress N2O emission in rice paddies?—A cross site field experiment from South China. *Ecological Engineering* 42, 168-173.

Liu, Y., Wen, C. and Liu, X. (2013). China's food security soiled by contamination. *Science* 339, 1382-1383.

Liu, Z., Niu, W., Chu, H., Zhou, T. and Niu, Z. (2018). Effect of the Carbonization Temperature on the Properties of Biochar Produced from the Pyrolysis of Crop Residues. *BioResources* 13, 3429-3446.

Long, H. and Qu, Y. (2018). Land use transitions and land management: A mutual feedback perspective. *Land use policy* 74, 111-120.

Maurer, D., Koziel, J., Kalus, K., Andersen, D. and Opalinski, S. (2017). Pilot-scale testing of non-activated biochar for swine manure treatment and mitigation of ammonia, hydrogen sulfide, odorous volatile organic compounds (VOCs), and greenhouse gas emissions. *Sustainability* 9, 929.

Musa, S.D., Zhonghua, T., Ibrahim, A.O. and Habib, M. (2018). China's energy status: A critical look at fossils and renewable options. *Renewable and Sustainable Energy Reviews* 81, 2281-2290.

Naeem, M.A., Khalid, M., Aon, M., Abbas, G., Tahir, M., Amjad, M., Murtaza, B., Yang, A. and Akhtar, S.S. (2017). Effect of wheat and rice straw biochar produced at different temperatures on maize growth and nutrient dynamics of a calcareous soil. *Archives of Agronomy and Soil Science* 63, 2048-2061.

Ng, W.C., You, S., Ling, R., Gin, K.Y.-H., Dai, Y. and Wang, C.-H. (2017). Co-gasification of woody biomass and chicken manure: Syngas production, biochar reutilization, and cost-benefit analysis. *Energy* 139, 732-742.

Oleszczuk, P., Jośko, I. and Kuśmierz, M. (2013). Biochar properties regarding to contaminants content and ecotoxicological assessment. *Journal of Hazardous Materials* 260, 375-382.

Owens, G.M. (2007). Analyzing impacts of bioenergy expansion in China using strategic environmental assessment. *Management of Environmental Quality: An International Journal* 18, 396-412.

Pacioni, T.R., Soares, D., Di Domenico, M., Rosa, M.F., Moreira, R.d.F.P.M. and José, H.J. (2016). Bio-syngas production from agro-industrial biomass residues by steam gasification. *Waste Management* 58, 221-229.

Panahi, H. K. S., Dehhaghi, M., Ok, Y. S., Nizami, A. S., Khoshnevisan, B., Mussatto, S. I., ... & Lam, S. S. (2020). A comprehensive review of engineered biochar: production, characteristics, and environmental applications. *Journal of Cleaner Production*, 122462.

Palansooriya, K.N., Ok, Y.S., Awad, Y.M., Lee, S.S., Sung, J.-K., Koutsospyros, A. and Moon, D.H. (2019). Impacts of biochar application on upland agriculture: A review. *Journal of environmental management* 234, 52-64.

Pan, J., Ma, J., Liu, X., Zhai, L., Ouyang, X. and Liu, H. (2019). Effects of different types of biochar on the anaerobic digestion of chicken manure. *Bioresource Technology* 275, 258-265.

Pan, X., Chen, W., Wang, L., Lin, L. and Li, N. (2018). The role of biomass in China's long-term mitigation toward the Paris climate goals. *Environmental Research Letters* 13, 124028.

Phillips, C.L., Trippe, K., Reardon, C., Mellbye, B., Griffith, S.M., Banowetz, G.M. and Gady, D. (2018). Physical feasibility of biochar production and utilization at a farm-scale: A case-study in non-irrigated seed production. *Biomass and Bioenergy* 108, 244-251.

Piovani, C. (2017). The "Greening" of China: Progress, Limitations, and Contradictions. *Journal of Contemporary Asia* 47, 93-115.

Qian, L., Chen, L., Joseph, S., Pan, G., Li, L., Zheng, J., Zhang, X., Zheng, J., Yu, X. and Wang, J. (2014). Biochar compound fertilizer as an option to reach high productivity but low carbon intensity in rice agriculture of China. *Carbon Management* 5, 145-154.

Qifa, Z., Houge, B.A., Zhaohui, T., Bin, G. and Guodong, L. (2018). An in-situ Technique for Producing Low-Cost Agricultural Biochar. *Pedosphere* 28, 690-695.

Qin, X., Li, Y.e., Wang, H., Liu, C., Li, J., Wan, Y., Gao, Q., Fan, F. and Liao, Y. (2016). Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: A four-year case study in south China. *Science of the Total Environment* 569, 1390-1401.

Ren, H., Li, Z.a., Guo, Q. and Wang, Q. (2008). Bioenergy: future direction of China's energy and environment integrated strategy. *AMBIO: A Journal of the Human Environment* 37, 136-139.

Shafeeyan, M.S., Daud, W.M.A.W., Houshmand, A. and Shamiri, A. (2010). A review on surface modification of activated carbon for carbon dioxide adsorption. *Journal of Analytical and Applied Pyrolysis* 89, 143-151.

Shan, M., Li, D., Jiang, Y. and Yang, X. (2016). Re-thinking china's densified biomass fuel policies: Large or small scale? *Energy Policy* 93, 119-126.

Shan, M., Wang, P., Li, J., Yue, G. and Yang, X. (2015). Energy and environment in Chinese rural buildings: Situations, challenges, and intervention strategies. *Building and Environment* 91, 271-282.

Shi, X. (2019). Inequality of opportunity in energy consumption in China. *Energy Policy* 124, 371-382.

Sui, F., Zuo, J., Chen, D., Li, L., Pan, G. and Crowley, D.E. (2018). Biochar effects on uptake of cadmium and lead by wheat in relation to annual precipitation: a 3-year field study. *Environmental Science and Pollution Research* 25, 3368-3377.

Sun, X., Shan, R., Li, X., Pan, J., Liu, X., Deng, R. and Song, J. (2017). Characterization of 60 types of Chinese biomass waste and resultant biochars in terms of their candidacy for soil application. *Gcb Bioenergy* 9, 1423-1435.

Tan, Z., Lin, C. S., Ji, X., & Rainey, T. J. (2017). Returning biochar to fields: A review. *Applied Soil Ecology*, 116, 1-11.

Tsai, W.-T., Liu, S.-C., Chen, H.-R., Chang, Y.-M. and Tsai, Y.-L. (2012). Textural and chemical properties of swine-manure-derived biochar pertinent to its potential use as a soil amendment. *Chemosphere* 89, 198-203.

Wang, C., Zhang, L., Yang, S. and Pang, M. (2012). A hybrid life-cycle assessment of nonrenewable energy and greenhouse-gas emissions of a village-level biomass gasification project in China. *Energies* 5, 2708-2723.

Wang, G., Li, Q., Dzakpasu, M., Gao, X., Yuwen, C. and Wang, X.C. (2018a). Impacts of different biochar types on hydrogen production promotion during fermentative co-digestion of food wastes and dewatered sewage sludge. *Waste Management* 80, 73-80.

Wang, L., Li, L., Cheng, K., Ji, C., Yue, Q., Bian, R. and Pan, G. (2018b). An assessment of emergy, energy, and cost-benefits of grain production over 6 years following a biochar amendment in a rice paddy from China. *Environmental Science and Pollution Research*, 1-14.

Wang, L., Wang, Y., Ma, F., Tankpa, V., Bai, S., Guo, X., & Wang, X. (2019). Mechanisms and reutilization of modified biochar used for removal of heavy metals from wastewater: a review. *Science of the Total Environment*, 668, 1298-1309.

Wang, W., Guo, L., Li, Y., Su, M., Lin, Y., De Perthuis, C., Ju, X., Lin, E. and Moran, D. (2015). Greenhouse gas intensity of three main crops and implications for low-carbon agriculture in China. *Climatic Change* 128, 57-70.

Wang, X., Zhao, X., Zhang, Z., Yi, L., Zuo, L., Wen, Q., Liu, F., Xu, J., Hu, S. and Liu, B. (2016). Assessment of soil erosion change and its relationships with land use/cover change in China from the end of the 1980s to 2010. *Catena* 137, 256-268.

Wang, Y.-S., Li, D.-B., Zhang, F., Tong, Z.-H. and Yu, H.-Q. (2018c). Algal biomass derived biochar anode for efficient extracellular electron uptake from Shewanella oneidensis MR-1. *Frontiers of Environmental Science & Engineering* 12, 11.

Wang, Y., Hu, Y., Zhao, X., Wang, S. and Xing, G. (2013). Comparisons of biochar properties from wood material and crop residues at different temperatures and residence times. *Energy & Fuels* 27, 5890-5899.

Waqas, M., Aburiazaiza, A., Miandad, R., Rehan, M., Barakat, M. and Nizami, A. (2018). Development of biochar as fuel and catalyst in energy recovery technologies. *Journal of Cleaner Production* 188, 477-488.

Wei, S., Zhu, M., Song, J. and Peng, P.a. (2017). Comprehensive characterization of biochars produced from three major crop straws of China. *BioResources* 12, 3316-3330.

Wu, C., Yin, X., Ma, L., Zhou, Z. and Chen, H. (2008). Design and operation of a 5.5 MWe biomass integrated gasification combined cycle demonstration plant. *Energy & Fuels* 22, 4259-4264.

Xin, D., Xian, M. and Chiu, P.C. (2019). New methods for assessing electron storage capacity and redox reversibility of biochar. *Chemosphere* 215, 827-834.

Yang, J. and Chen, B. (2014). Global warming impact assessment of a crop residue gasification project—a dynamic LCA perspective. *Applied Energy* 122, 269-279.

Yang, J., Song, K., Hou, J., Zhang, P. and Wu, J. (2017). Temporal and spacial dynamics of bioenergy-related CO2 emissions and underlying forces analysis in China. *Renewable and Sustainable Energy Reviews* 70, 1323-1330.

Yang, Q., Han, F., Chen, Y., Yang, H. and Chen, H. (2016). Greenhouse gas emissions of a biomass-based pyrolysis plant in China. *Renewable and Sustainable Energy Reviews* 53, 1580-1590.

Yang, Q., Zhou, H., Zhang, X., Nielsen, C.P., Li, J., Lu, X., Yanga, H. and Chen, H. (2018). Hybrid life-cycle assessment for energy consumption and greenhouse gas emissions of a typical biomass gasification power plant in China. *Journal of Cleaner Production* 205, 661-671.

Yao, Z., Li, W., Kan, X., Dai, Y., Tong, Y.W. and Wang, C.-H. (2017). Anaerobic digestion and gasification hybrid system for potential energy recovery from yard waste and woody biomass. *Energy* 124, 133-145.

Ye, S., Zeng, G., Wu, H., Liang, J., Zhang, C., Dai, J., Xiong, W., Song, B., Wu, S. and Yu, J. (2019). The effects of activated biochar addition on remediation efficiency of co-composting with contaminated wetland soil. *Resources, Conservation and Recycling* 140, 278-285.

Ye, S., Zeng, G., Wu, H., Zhang, C., Dai, J., Liang, J., Yu, J., Ren, X., Yi, H. and Cheng, M. (2017). Biological technologies for the remediation of co-contaminated soil. *Critical reviews in biotechnology* 37, 1062-1076.

Yin, X.L., Wu, C.Z., Zheng, S.P. and Chen, Y. (2002). Design and operation of a CFB gasification and power generation system for rice husk. *Biomass and Bioenergy* 23, 181-187.

You, S., Ok, Y.S., Chen, S.S., Tsang, D.C., Kwon, E.E., Lee, J. and Wang, C.-H. (2017a). A critical review on sustainable biochar system through gasification: energy and environmental applications. *Bioresource Technology* 246, 242-253.

You, S., Ok, Y.S., Tsang, D.C., Kwon, E.E. and Wang, C.-H. (2018). Towards practical application of gasification: a critical review from syngas and biochar perspectives. *Critical Reviews in Environmental Science and Technology*, 1-49.

You, S., Tong, H., Armin-Hoiland, J., Tong, Y.W. and Wang, C.-H. (2017b). Techno-economic and greenhouse gas savings assessment of decentralized biomass gasification for electrifying the rural areas of Indonesia. *Applied Energy* 208, 495-510.

You, S. and Wang, X. (2019). On the Carbon Abatement Potential and Economic Viability of Biochar Production Systems: Cost-Benefit and Life Cycle Assessment *Biochar from Biomass and Waste*, 385-408): Elsevier.

Zhang, A., Bian, R., Li, L., Wang, X., Zhao, Y., Hussain, Q. and Pan, G. (2015a). Enhanced rice production but greatly reduced carbon emission following biochar amendment in a metal-polluted rice paddy. *Environmental Science and Pollution Research* 22, 18977-18986.

Zhang, A., Bian, R., Pan, G., Cui, L., Hussain, Q., Li, L., Zheng, J., Zheng, J., Zhang, X. and Han, X. (2012). Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: a field study of 2 consecutive rice growing cycles. *Field Crops Research* 127, 153-160.

Zhang, A., Zhou, X., Li, M. and Wu, H. (2017). Impacts of biochar addition on soil dissolved organic matter characteristics in a wheat-maize rotation system in Loess Plateau of China. *Chemosphere* 186, 986-993.

Zhang, F., Chen, X. and Vitousek, P. (2013). Chinese agriculture: An experiment for the world. *Nature* 497, 33.

Zhang, J., Zhao, W., Zhang, H., Wang, Z., Fan, C. and Zang, L. (2018a). Recent achievement in enhancing anaerobic digestion with carbon-based functional materials. *Bioresource Technology*.

Zhang, L., Liu, Y. and Hao, L. (2016). Contributions of open crop straw burning emissions to PM2. 5 concentrations in China. *Environmental Research Letters* 11, 014014.

Zhang, L., Wang, C. and Bahaj, A. (2014a). Carbon emissions by rural energy in China. *Renewable Energy* 66, 641-649.

Zhang, R., Wei, T., Glomsrød, S. and Shi, Q. (2014b). Bioenergy consumption in rural China: Evidence from a survey in three provinces. *Energy Policy* 75, 136-145.

Zhang, W. and Tsang, D.C. (2019). Sludge-Derived Biochar and Its Application in Soil Fixation *Biochar from Biomass and Waste*, 239-253): Elsevier.

Zhang, W., Wang, C., Zhang, L., Xu, Y., Cui, Y., Lu, Z. and Streets, D.G. (2018b). Evaluation of the performance of distributed and centralized biomass technologies in rural China. *Renewable Energy* 125, 445-455.

Zhang, X., Zhong, T., Liu, L. and Ouyang, X. (2015b). Impact of soil heavy metal pollution on food safety in China. *PLoS One* 10, e0135182.

Zhang, Z., Zhu, Z., Shen, B. and Liu, L. (2019). Insights into biochar and hydrochar production and applications: A review. *Energy* 171, 581-598.

Zhao, F.-J., Ma, Y., Zhu, Y.-G., Tang, Z. and McGrath, S.P. (2014). Soil contamination in China: current status and mitigation strategies. *Environmental Science & Technology* 49, 750-759.

Zhao, X. (2018). Soil degradation through agriculture in China: its extent, impacts and implications for environmental law reform *International Yearbook of Soil Law and Policy 2017*, 37-63): Springer.

Zheng, R., Chen, Z., Cai, C., Tie, B., Liu, X., Reid, B.J., Huang, Q., Lei, M., Sun, G. and Baltrėnaitė, E. (2015). Mitigating heavy metal accumulation into rice (Oryza sativa L.) using biochar amendment—a field experiment in Hunan, China. *Environmental Science and Pollution Research* 22, 11097-11108.

Zhou, Z., Yin, X., Xu, J. and Ma, L. (2012). The development situation of biomass gasification power generation in China. *Energy Policy* 51, 52-57.

Zhu, Z., Jia, Z., Peng, L., Chen, Q., He, L., Jiang, Y. and Ge, S. (2018). Life cycle assessment of conventional and organic apple production systems in China. *Journal of Cleaner Production* 201, 156-168.

Zhuang, P., Zou, B., Li, N. and Li, Z. (2009). Heavy metal contamination in soils and food crops around Dabaoshan mine in Guangdong, China: implication for human health. *Environmental Geochemistry and Health* 31, 707-715.