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Environmental and economic assessment of crop residue competitive utilization for biochar, briquette fuel and combined heat and power generation

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ABSTRACT

Competitive utilization of straw is a challenge faced by developing countries such as China with the increase of crop production. Biochar, briquette fuel and combined heat and power generation are the three main new measures for straw utilization in recent years; however, there is still a knowledge gap for environmental and economic effects of these utilizations in China. To address this issue, combined life-cycle analysis and cost-benefit analysis was employed to assess the environmental impacts and economic benefits of biochar, briquette fuel and combined heat and power generation applications based on three cases in China. The results suggested that biochar was the most promising technology for straw utilization in China for its highest greenhouse gas mitigation potential i.e. −0.94 t CO_2 equivalent (CO_2e) per ton straw utilized and high profit with a net present value per ton straw of 20.98 U.S. dollars with the baseline of crop straw return including carbon revenue. Briquette fuel also deserves to achieve a best net present value ratio of 5.06 and GHG abatement potential being −0.9 t CO_2e t^{-1} straw. However, the waste of straw ash could bring some pollution risk without suitable treatment. The economic potential of the combined heat and power generation project that produces bioelectricity, is not considerable with a very low net present value ratio of 0.007 and a mitigation potential of −0.03 tCO_2e t^{-1} straw due to low energy utilization efficiency of direct combustion. Biochar could be one of the most potential economic and environmental sustainable straw utilization technologies in China though the wide production and application is still a big challenge in future.

1. Introduction

With the rapid increase in crop production in China, the biggest challenge is utilization of massive amount of crop straw after harvests. The straw amount had been increased to almost 0.82 billion tons in 2012; however, only 74% of all the straw was well utilized. There is still a large amount of straw (nearly one fourth) burned open air or discarded, which caused a lot of CO_2, Particulate Matter 2.5 (PM2.5), and black carbon emitted and resulted in severe environmental issues (NDRC, 2014; Shi et al., 2014). Straw incorporation was proposed as one of the considerable measures by Ministry of Agriculture of China due to its beneficial effect on soil organic carbon and crop production (MOA, 2006, 2011; Liu et al., 2013a). However, a recent questionnaire survey about the impacts of straw incorporation on agro-ecosystem in a city of northern China indicated that direct straw incorporation could aggravate the insect pests and plant diseases, resulting additional pesticide application and cost increase being almost 300–450 CNY ha^{-1} yr^{-1} (Li et al., 2013). Hence, seeking the better pathways for utilization crop straw is still a challenge for China's agriculture.

According to "US-China Joint Announcement on Climate Change" released in November 2014, China committed to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030 and achieve the peaking of CO_2 emissions around 2030 (Xinhua net, 2014). The utilization of straw as an energy resource is expected to become more commercial in the

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future, so straw comprehensive utilization should be given priority to develop as one of the potential carbon sink pathways (NDRC, 2014). However, crop straw is a scattered resource with a lower energy density and less efficient to store and transport (Hu et al., 2014). There had been some straw utilization pathways developed including straw pyrolysis, straw briquette fuel and bio-electricity generation in recent years.

Biochar amendment technology has been rapidly developed recently (Lehmann, 2007; Woolf et al., 2010). Biochar is a kind of carbon-rich solid formed by pyrolysis of biomass in the absence of oxygen (Lehmann and Joseph, 2009). According to many existing studies, biochar application to soil has been suggested as a climate change abatement measure which mitigates GHG emission by sequestering organic carbon in soil and mitigating N_2O emissions, while simultaneously providing energy and increasing crop yield (Woolf et al., 2010; Liu et al., 2013b). Nearly 0.25 million ton of straw had been treated by pyrolysis in Hunan, Hubei and Henan provinces in 2011 (EC-CAS, 2013). Briquette fuel is a technology to compress unshaped raw materials to solid fuel with higher density by means of drying, chopping and briquetting, which could save the costs of transportation and storage and improve combustion quality. This technology could apply not only in power generation through gasification, direct combustion and co-combustion, but also in industrial boilers, furnaces, heating boilers and other combustion equipment. According to the statistics, the total production of briquette fuel had increased to 3.82 million tons in China (EC-CAS, 2013). Bio-electricity generation using straw also attracts great attention to the public, and the government had proposed straw power generation as one of the key greenhouse gas mitigation technologies. China's installed capacity of straw power generation was increased to 5819 MW by 2012, and will be reached to 15000 MW by 2020 (Zhang et al., 2013a; Yang et al., 2013; NDRC, 2016).

Given these, there would be an urgent demand to give a comprehensive assessment including environmental and economic effects for these straw competitive utilizations. The life-cycle analysis was widely employed to assess the environmental sustainability of the straw utilization industries by taking all the environmental impacts in the whole life cycles into account (Shafie et al., 2014; Song et al., 2017). While the economic performances were often investigated by cost-benefit analysis through considering all the costs and benefits for the straw utilization industries (Xu et al., 2015; Mupondwa et al., 2017). Most studies focused on the environmental assessments of straw-based power generation recently (Sastre et al., 2013; Zhang et al., 2013a; Shafie et al., 2014). For example, Sastre et al. (2013) indicated that electricity generation from wheat straw could offset 60% of GHG emissions induced by natural gas based power generation in Spain using the life cycle assessments; and a study analyzed the environment impacts of rice straw-based power generation in Malaysia, which suggested that GHG emissions were much lower by 1.79 and 1.05 kg CO_2 equivalent (CO_2e)/kWh than coal-based and natural gas based power generation (Shafie et al., 2014). There were also some studies assessing the carbon abatements or economic benefits from straw-based briquette fuel or straw pyrolysis (Hu et al., 2014; Song et al., 2017). A life cycle assessment indicated that a reasonable GHG mitigation could be achieved by straw-based briquette fuel compared to the use of coal in China (Hu et al., 2014). Huo et al. (2017) assessed the environmental and economic performances of straw pyrolysis and resulted that a net profit of 87–141 Chinese yuan per ton straw and a net carbon abatement of 0.48–0.82 t CO_2e per ton straw could be obtained by different modes of straw pyrolysis. However, the comprehensive assessments including both economic and environmental performances for different straw competitive utilizations were still very limited though there had been some studies which began to focus on the comparisons of environmental and economic performances of different straw competitive utilizations (Clare et al., 2015; Xu et al., 2015; Mupondwa et al., 2017). For example, Clare et al. (2015) conducted a comprehensive assessments of straw pyrolysis, straw based power generation and straw based briquette fuel. Nevertheless, more indicators and local parameters should be developed and adopted in further assessments, and there would be still an important issue of the set of baseline scenario should be addressed for straw competitive utilizations.

This study aims to address these issues by evaluating the economic efficiency and environmental impacts of major crop straw utilizations based on life cycle assessment and cost-benefit assessment with field investigation. Straw return was taken into account the baseline scenario according to China's practical situation. Some economic parameters were proposed and recent regional specific emission factors were adopted. The environmental and economic sustainability of these straw competitive utilization projects in China was also discussed.

2. Materials and methods

2.1. Sites description

2.1.1. Biochar (BC)

"*Sanli New Energy Plant*" located in Henan Province was selected as a case due to its success operation. "*Sanli New Energy Plant*" was also listed as a typical case for low carbon technology by National Development and Reform Commission, China (NDRC, 2014), this plant had almost 14 years of history. Henan Province, located in the Central Great Plain of Yellow River-Huaihe River in North China, had the grain yield being 6.29 million tons in 2012 including 63% of wheat and 32% of corn. Hence, corn and wheat straw were the main feedstock for this plant. Farmers nearby were the main consumers of electricity and biochar, while researchers and other fertilizer plants were also the consumers of biochar. With increasing attention of carbon sequestration and crop production improvement by biochar soil amendment, the economic feasibility had been proved quite good. The prices of electricity and biochar were 0.11 U.S. dollars kWh^{-1} and 266.67 U.S. dollars t^{-1}, respectively. Other parameters used in this evaluation are also listed in Table 1.

2.1.2. Straw-based briquette fuel (BF)

"*Green Bioenergy Plant*" located in Jiangsu Province was selected as a case to assess the environmental and economic effects of straw-based briquette fuel. Jiangsu is a large province located in the Yangtze River Delta region of China, and the typical cropping system is rice-wheat rotation in Jiangsu Province. In Jiangsu province, almost 50% of the crop straw are available for comprehensive use. Jiangsu had 9 years' history to produce the straw as briquette fuel, and also occupied the biggest share of briquetting fuel market in China according to the statistical data (EC-CAS, 2013). For "*Green Bioenergy Plant*", the main feedstock is the straw of rice and wheat. With lots of co-operative partner, the briquette fuel is used as heat fuel for school and other enterprises replacing coal and the economic feasibility is well. The initial capital cost of this plant was about 0.89 million U.S. dollars and the annual feedstock was 30 thousand ton of straw. The market price of briquette fuel was $88.89 per ton based on the energy density of straw briquette and the energy value of coal. The main economic parameters are listed in Table 1.

2.1.3. Combined heat and power generation (CHP)

"*Guo Zhen bioelectricity plant*" located in Anhui Province was selected as a case for straw use of combined heat and power