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RESEARCH ARTICLE

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Environmental, social, and economic assessment of energy utilization of crop residue in China

Abstract This paper aims to discuss an environmental, social, and economic analysis of energy utilization of crop residues from life cycle perspectives in China. The methodologies employed to achieve this objective are environmental life cycle assessment (E-LCA), life cycle cost (LCC), and social life cycle assessment (S-LCA). Five scenarios are developed based on the conversion technologies and final bioenergy products. The system boundaries include crop residue collection, transportation, pre-treatment, and conversion process. The replaced amounts of energy are also taken into account in the E-LCA analysis. The functional unit is defined as 1 MJ of energy produced. Eight impact categories are considered besides climate change in E-LCA. The investment capital cost and salary cost are collected and compared in the life cycle of the scenarios. Three stakeholders and several subcategories are considered in the S-LCA analysis defined by UNEP/SETAS guidelines. The results show that the energy utilization of crop residue has carbon emission factors of 0.09–0.18 kg (CO_2 eq per 1 MJ), and presents a net carbon emissions reduction of 0.03–0.15 kg (CO_2 eq per 1 MJ) compared with the convectional electricity or petrol, but the other impacts should be paid attention to in the biomass energy scenarios. The energy utilization of crop residues can bring economic benefit to local communities and the society, but the working conditions of local workers need to be improved in future biomass energy development.

Keywords crop residue, life cycle assessment, life cycle cost, social life cycle assessment, energy production

1 Introduction

One of the major objectives of energy development is to become a low-carbon and secure energy system [1,2]. Biomass, especially crops and wood residues, is the first-ever fuel consumed by human beings before the first Industrial Revolution in the 18th century. In the 21st century, establishing a sustainable energy system has become a global objective of energy technology development, where renewable energy is replacing fossil fuels for the production of heat, electricity, and transportation fuels under the pressure of climate change, especially global warming issues [3–5]. Not just because biomass resources are available in large quantity, but also because they are suitable for the sustainable energy supply of transportation fuels, electricity, and heat [6].

Even though crops and timbers are ultimately produced by plants absorbing CO_2 from the atmosphere in the growth phase, the environmental consequence of their energy utilization depends on the time perspective of carbon exchange with atmospheric CO_2 and plant ecology [7,8]. Meanwhile using biomass as a material for producing energy allows the reduction of fossil fuel consumption, but the uncertainty of addressing potential CO_2 emissions from land-use change is still the obstacle of biofuel development [9], not to mention that the promotion of energy production from plants (crops, trees) could cause

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impacts on indirect land-use change and biodiversity regionally and globally [10,11]. On the contrary, crop residue is normally recognized as a co-production of grain production, where food and animal feed are the main products of agricultural cropping activity. The application of crop residues as a material to produce renewable energy will not compete with food or feed production.

In regard to energy utilization of biomass resources, efforts were made in most of the studies on the potential energy production and associated environmental impacts, which were typically CO_2 emissions [12,13]. Cherubini et al. addressed energy production and potential CO_2 emissions from biomass utilization by environmental life cycle assessment (E-LCA) [14,15]. The environmental consequences of bioenergy production from different biomass resources were assessed and compared considering the life farming practice and conversion technologies from the life cycle perspectives [16,17]. It is globally acknowledged that different conversion technologies will lead to different costs, and different environmental impacts [18,19]. Many studies can be found for extending E-LCA toward the economic and social performance of biofuels in different regions around the world [20–22]. Few attempts can be found for the life cycle sustainability assessment framework proposed for the sustainable of bioenergy development [23,24]. Even though energy utilizations of biomass resources were not always ‘carbon neutral’ [14], the use of crop residues was considered as ‘carbon negative’ by replacing fossil fuels [15]. However, the research considering life cycle cost (LCC) and social life cycle assessment (S-LCA) into environmental LCA analysis of crop residue is currently insufficient.

In 2010, there were about 94 million tons of primary crop residues profitable to collect at farm gate feedstock in China. By 2030, estimated supplies would go up to 180 million tons of dry crop residues [25]. The largest quantities of crop residues are from grain crops. More than three-fourths of crop residues are corn stover, followed by wheat straw, which accounts for about a fifth of the total quantity. A variety of development stages occupy in various commercial uses for crop residues. In the past, crop residues were generally used for heat production and animal feed in the countryside in China [26,27]. Several companies that made fiberboards from straw have emerged in recent years with mixed success [28]. In China, the low carbon development strategy has been a part of national development planning for decades [29,30]. The potential role of biomass energy in the national energy supply was addressed [27,31], and further intensified by integrating ethanol for mobility in 2017 [32]. In recent years, producing renewable energy and other valuable bioproducts by crop residues has received remarkable attention [33,34]. Crop residues are recognized as one of the best sources for renewable energy and can produce electricity, heat and liquid fuels [35]. With the development of the biofuel conversion technology, intensive attention is paid to producing bioethanol and biomethanol by crop residues. Additionally, crop residues are important materials to make synthetic gas (consisting of carbon monoxide and hydrogen) in the gasification process and then to produce electricity, chemicals, and liquid fuel [36,37]. Therefore, it is very important for decision-makers to evaluate the technologies and products using comprehensive assessment from social, economic, and environmental perspectives. E-LCA, LCC and S-LCA are used to conduct the analysis.

The aim of this paper is to present an overview picture of the environmental, economic, and social consequences of energy utilization of crop residues from the life cycle perspective. First, the material and methods employed for utilization of crop residues are considered. The system boundary is built and the process of data collection is described. Next, the results from the environmental impact, cost analysis, and social impact are presented. Lastly, the research findings and recommendations for future studies are conducted.

2 Materials and methods

E-LCA as an environmental assessment tool, has been well developed, structured by ISO and globally implemented in the processing of product [38,39]. Similarly, LCC has been developed to evaluate the viability and attractiveness of projects from the perspective of economy. The methodology of S-LCA is still in the early stage of development compared with E-LCA and LCC [40]. Since this paper considers the three dimensions of sustainability, identified by the three assessment methods, it is important that the analysis should be maintained through the whole life cycle of the processing of crop residues. Even though life cycle methodologies cannot capture the entire breadth of sustainable development, they can provide information on the potential impacts from the life cycle of an energy unitisation of crop residue [41]. Life cycle methodologies are described starting with the goal and scope definition.

2.1 Goal and scope definition

To give a broader picture of the energy use of crop residues, the objectives of this paper are to identify the environmental impacts of energy utilization technologies of crop residues, and to analyze the economic and social impacts on workers, local communities, and the society. In this paper, the crop residues are converted into electricity, hydrogen, and biofuels. Electricity is consumed by residences through the electric grid. Hydrogen and biofuel are used as fuels for vehicles to replace fossil fuel, which is gasoline in this paper.

2.1.1 Functional unit

The functional unit is the quantified measure of the product performance system, which ensures the fair comparison of the products/services at the same level. It is quite straightforward to link the results of both E-LCA, and LCC to the same functional unit. As the systems that were subject to this paper were located in China, the US Dollar ($) is selected as the currency. It may be difficult to define the functional unit for S-LCA the same as E-LCA and LCC [42], as a characteristic of social impacts. For this paper, the functional unit considered for the assessment was to produce 1 MJ of energy for the consumer. For the assessment of social impact, the result will be presented as a qualitative survey result.

2.1.2 System boundary

The system boundary for a life cycle analysis determines the scope to conduct and facilitate the evaluations. Nevertheless, the system boundary should involve the unit processes which have a potentially considerable impact on emissions from at least one of the three aspects of sustainability [43]. So the system boundary need to be defined as similarly as possible for the social, economic, and environmental assessment [44]. A different definition of system boundary has a remarkable impact on the results of E-LCA, LCC, and S-LCA. Ideally, the three analyses should be conducted in the same system boundary.

This paper basically covers the processes from cradle to grave starting from crop residue collection, transportation to residue pre-treatment plant, and conversion plant. The investigated crop residues are mainly corn stover and wheat straw, as corn and wheat are the main cereal crops cultivated in China [25,45]. Pre-treatment here refers to physical pre-treatment, including dehydrating and compressing the residues to fuel pellets [46]. After that, the pre-treated residues are transported to conversion plants and converted to different kinds of energy products. With respect to recommendations for future biomass energy regulations, it is important to investigate crop conversion facilities located in different parts of China, so that the results can represent the situation of biomass energy utilization in general. The final energy products based on crop residue will be distributed to consumers to replace conventional energies. The system boundary of E-LCA starts from the beginning of the diagram using crop residues, and supplying products and services at the end (Fig. 1). In this system, several conversion technologies are combined to jointly be applied to produce electricity, heat, and biofuels. The first step of the transport process is to bring crop residues from the field to the pre-treatment plants (compressing, dehydration, and pelleting). The final step is to transport the pellets to the biomass conversion plant.

LCC covers the costs associated with the life cycle of bioproducts by all the actors, who are getting involved both directly or indirectly in their whole life process. In this paper, the prices of the bioproducts determine the income/salary of the actors from different stages within the system boundary. LCC denominates flows by monetary terms whereas E-LCA does so by physical quantities such as mass, energy, and volume.

LCC shares the system boundary with E-LCA outlined in gray color. The boundary is based on the principles of life cycle thinking from residues removal and collection, pre-treatment, residues, transportation, conversion processes, and bio-energy products (electricity, heat, hydrogen and bioethanol). Considering the S-LCA methodology and its data availability, all three assessments are recommended

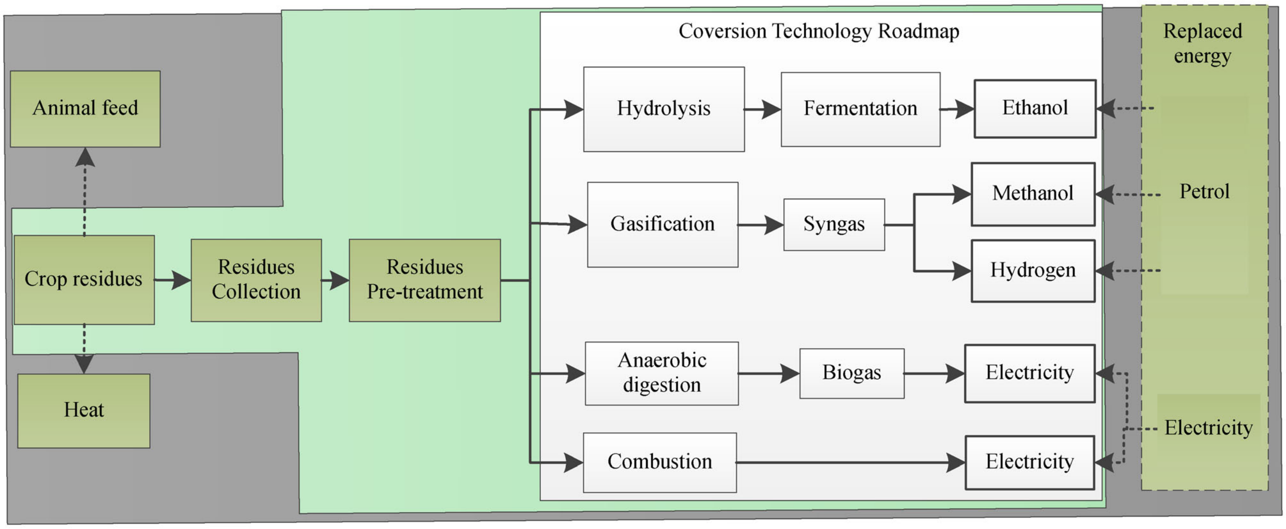

Fig. 1 System boundary of crop residues energy utilization (The gray box represents the system boundary for E-LCA and LCC, while the green box refers to the system boundary for S-LCA.).

ideally to have the same system boundary. Because S-LCA currently has no systematic databases, it is impossible to make a detailed analysis of all the processes along the life cycle of fossil fuels. Therefore, the upstream of crop residue used for animal feed and heat is not included in the social assessment of product systems, including data collection (preferably at the local level) and system boundary.

Even though the LCC and E-LCA share the same system boundary, they are based on different functional units and purposes. In the E-LCA analysis, the impact result is directly reflected by the impacts of the elements in the studied chain process. In the LCC analysis, the price reflects directly not only the elements of one chain process, but also the elements of other chain processes indirectly. Although only residue collection, transportation, and application prices are considered, it is assumed that producers also include all the costs in the processes of the life cycle of the product. The collection cost includes collection cost and storage cost. The cost for interior allocation of distribution of the bioenergy is excluded. Two different shared systems is used to show the specific system boundary for S-LCA and for both E-LCA and LCC. Moreover, only those stages and substages within crop residues collection, transportation, and conversion in S-LCA are considered. There will be some overlap between LCC and S-LCA, as the interior cost in LCC is also analyzed in S-LCA by the job category meanwhile. The stakeholders in S-LCA include workers (by contractor, subcontractor, etc.), the local community (working conditions, etc.), and the society (health and safety, etc.).

2.1.3 Impact category

The following impact categories are included in E-LCA: Climate change (global warming potential in kg (equivalent of CO_2), ozone depletion (emission of ozone-depleting potential, in kg CFC-11 equivalents, 20 years); Acidification (emission of acidifying gases, in kg (equivalent of SO_2), eutrophication (oxygen consumption potential, in kg (equivalent of P), human toxicity (comparative toxic unit for humans, in CTUh). In addition, this paper includes two categories that reflect the use of mineral, fossil and renewable resource depletion, expressed in kg (equivalent of Sb), and water resource depletion, expressed in m^3 (equivalent of water). The impact assessment method of ILCD is applied to do the assessment, and Simapro is used for the calculation.

The guideline recommends that all data, whether quantitative or qualitative, should be collected throughout the life cycle. At present, S-LCA is facing several challenges such as the selection and the analysis of social indicators, functional units, system boundaries, and the impact assessment method. The impact categories that are appropriate for a particular case study must be identified from the numerous social indicators available in Refs. [47,48]. Five social impact stakeholders are identified for social life cycle assessment, which are workers, local communities, society, consumers, and value chain [48]. The employment opportunities are the focusing of most current S-LCA studies [49]. Considering the limitation of the S-LCA methodology in practice, the categories are screened into three stakeholders and several subcategories. The three stakeholders are workers, local communities, and society. First, it is noted that the paper does intend neither to present a complete social assessment of energy use of crop residue nor to provide S-LCA results that are comprehensive enough for clear decision support regarding crop residue for energy use outside of China. In this paper, the consumer has been assumed as the same consumer of energy products (electricity, fuels) that are the same as those from other energy sources. So, the stakeholder of consumer is not included in this paper. The stakeholder group of value chain actors are not considered, as all subcategories of this group focus on the behavior of single companies. Each company has its own value chain, which is beyond the objective of this paper.

2.2 Scenarios analyses

The main biomass energy products are power/heat and transportation fuels. The roadmap of the crop conversion technology is classified into two groups: thermo-chemical (combustion, pyrolysis, gasification, and liquefaction) and biochemical/biological (digestion and fermentation) [50]. In this paper, five scenarios are developed based on the conversion technology and the final biofuel products based on the IPCC report (Table 1). The final product is electricity in Scenario S1 and Scenario S2, while the conversion technology is the thermo-chemical one and the bio-chemical one respectively. In Scenario S1, crop residue is burned directly to produce heat and steam which are

Table 1 Formulation of five scenarios related to conversion technologies and final products

Scenario	Source	Conversion technology	Intermediate product	Final product
S1	Residue	Combustion		Electricity
S2	Residue	Anaerobic digestion	Biogas, SNG	Electricity
S3	Residue	Gasification	Syngas	Hydrogen
S4	Residue	Gasification	Syngas	Methanol
S5	Residue	Hydrolysis/fermentation		Ethanol

used to produce electricity. This is the most common technology in operation in China. In Scenario S2, crop residue is converted to biogas by anaerobic digestion. This biogas can be produced in small scale and used for cooking or heating in rural areas in China. It can also be produced in a large plant and works as an energy source to generate electricity. Both S1 and S2 have been in operation and producing electricity for decades in China. Besides electricity as the final product, biofuels and green hydrogen have been attracting more attention. Biomass can produce synthetic gas and CO_2 through gasification. To comply with stringent emission standards, syngas is becoming increasingly important for the production of cleaner fuels. It is the intermediate energy carrier for producing second-generation biofuels like methanol. In Scenario S3 and Scenario S4, syngas is converted into hydrogen and methanol respectively, which can be used to power internal combustion engines in motor vehicles. In Scenario S5, ethanol is the final product from the hydrolysis and fermentation process.

2.3 Inventory and data collection

In this phase, data collection and calculation procedures are mainly focused on aiming to provide a detailed description of the inputs of raw material and fuels and the outputs of electricity, hydrogen, methanol, and ethanol. The data used in E-LCA-based information are classified into two categories: specific data referred to as primary data and selected secondary data referred to as generic data. As a general rule, specific data has been used when available. Generic data has been used in cases where there is a lack of specific data or if a product consists of many components.

The data are collected through a questionnaire survey and interview of the project manager for the conversion technology information as well as material and resource consumption (Table 2). For E-LCA, primary data from three regions across the country was used, whereas the secondary data were mainly of country-specific or region-specific origin. For LCC, all data and prices used for crop residue collection and transportation were specific. The cost of electricity and biofuel product is the contemporary national price. The market price of the hydrogen produced from renewable energy sources are not available in China. Even though hydrogen has been used in different industries e.g., ammonia, more than 99% of hydrogen currently in use is produced from gasifying or pyrolyzing of coal and steam reforming of natural gas. To avoid misleading with comparing price at different market levels, LCC analysis does not include S3. Regarding S-LCA, not only are quantitative data used, as is the case of E-LCA and LCC.

The questionnaire survey has been sent to the crop residues collection agents and plants in different municipalities, cities, and provinces. Insufficient data are remedied with the data collected from the literature and Ecoinvent database.

The cost applies to the period of 2010 to 2015. It has to be noted that the Chinese government subsidized the electricity generated from biomass. From the consumers' perspective, the price of energy products they pay is the market price, which combines product cost, distribution cost, and subsidies.

The indicator in S-LCA is generally challenging as databases compared to those available for E-LCA. Moreover, the data collected on-site of a conversion plant is always influenced by the individual local context. The aim of S-LCA is to analyze the potential impacts of the life

Table 2 Primary data collection of E-LCA, LCC, and S-LCA from stakeholders

Techniques	Project information	Data source
E-LCA	General project information	Site survey, Refs. [27,31,51]
	Total resource consumption	Site survey, Refs. [27, 31, 51]
	Total energy production	Site survey, Refs. [27,31,51]
	Material input and output from the plant	Site survey, Refs. [27,31,51]
	Resource collection	Site survey,
	Transportation	Site survey
	Replaced fuel	Eco invent database [52]
LCC	Capital investment	Site survey
	Residues cost	Site survey
	Labor cost	Site survey
	Transportation cost	Site survey
	Conversion plant cost	Refs. [27,31,51]
S-LCA	Job creation	Site survey
	Physical working condition	Site survey
	Health and safety	Refs. [27,31,51]

cycle of crop residues on energy use. The activities of crop residue collection and transportation occur in rural areas and the main stakeholders are the local farmers, which are not included in the national statistics salary [53]. The current agriculture farming activity is on a small scale based on family labor [54]. Therefore, the data are not available in the current Social Hotspot Database [55]. The approach to data collection for social impacts is through questionnaire surveys of farmers and interviews of agents and managers (see Electronic Supplementary Material). There are 1000 surveys sent out, including 400 in town, and 600 for the countryside divided into 23 locations in 3 provinces, named Henan, Shandong, and Hebei. The reason for choosing these three regions for the surveys is that these are the regions with larger agriculture activities in China. 921 surveys were answered and received. Of all the surveys received, the number of replies from men is 603, accounting for 65.5% while that from women is 318, accounting for 34.5%. The number of the respondents aging from 16 to 30 is 128, accounting for 13.9%; that aging from 31 to 50 is 541, accounting for 58.7%; that aging from 51 to 60 is 160, accounting for 17.4%; and that aging over 60 is 82, accounting for 8.2%. In the countryside, 95.3% of the survey questionnaires were answered with a positive opinion regarding the energy use of crop residues, while in cities, only 2.8% of the survey with a positive attitude.

2.4 Impact assessment

The impact assessment is a process to extract essential information from an inventory of technology/product to the results of the impact. Considering the quantitative nature of E-LCA, LCC, and S-LCA and the inventory data, different impact methods are used. The methodology of ILCD 2011 calculates the environmental impact while the LCA software Simapro is used to calculate environmental impact. The inventory costs are aggregated to provide a useful measure for assessing economic impacts. The S-LCA approach used is described as 'a potential social impacts' assessment technique that aims to assess the social aspects through the life cycle of the process [56]. The social impact inventory result will be conducted in qualitative analysis.

3 Results and discussion

3.1 Life cycle impact assessment result

One of the primary objectives of this paper is to understand the contribution of specific life cycle activities to the overall environmental performance of crop residues energy utilization. The life cycle environmental characterization results computed for the biofuel and bioelectricity scenarios are presented in Figs. 2 and 3. The results refer to the biofuels and electricity products, respectively. As observed, relevant differences are found for the five scenarios. For environmental impact, the entire energy utilization scenarios emit from 0.09 kg to 0.18 kg (equivalent of CO_2 per 1 MJ) of the energy produced. If considering the substituted energy, the entire GHG emissions are from –0.15 kg to –0.03 kg per 1 MJ of energy produced, which can be seen in Fig. 2. Note that the potential global warming impact obtained for the biofuel scenario indicates a virtual desirable impact, which is due to the purification of biofuel ready for transportation. The two carbon negative scenarios are Scenario S2 and Scenario S3. In Scenarios S1, S3 and S5, the largest carbon emissions come from the stage of crop residue collection which accounts for 68%, 61%, and 58% of the total impacts respectively. For Scenarios S2 and S4, the major carbon emissions come from the conversion processes, which account for 56% to 63% of total carbon emissions respectively.

In regard to other impact categories besides climate change, the impact results of particulate matter are between 6.82×10^{-5} kg $PM_{2.5}$ eq and 6.17×10^{-4} kg $PM_{2.5}$ eq in the five scenarios. The impact results of photochemical ozone formation are between 0.002 kg NMVOC eq and 0.015 kg NMVOC eq. The impact results of terrestrial eutrophication are between 0.004 mol and 0.015 mol N eq in the five scenarios. The characterization results of the impact

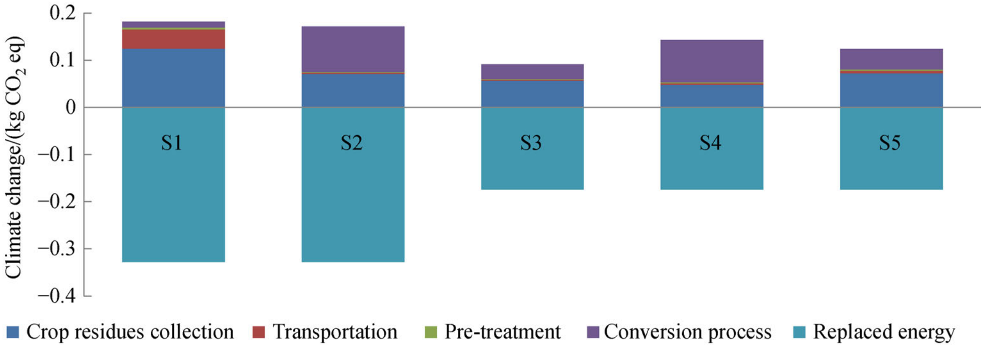

Fig. 2 Results of climate change of five energy application scenarios of crop residues.

categories of the entire life cycle are demonstrated in Fig. 3.

From Fig. 3, the major impacts of the 7 impact categories coming from the stage of crop residues collection in scenarios of S1, S3, S4 and S5 we can get that. In Scenario S1, the stage of crop residues collection and transportation accounts for more than 90% of the total impacts of climate change, ozone depletion, particulate matter, and terrestrial eutrophication. The reason for this is the low efficiency of residue collection and transport from the fields to the pre-treatment plants. The collection and transportation of biomass play an important part in the entire biomass to energy chain [57]. In Scenario S2, the stage of the conversion process has the largest impact in the other life stages. The environmental consequences of the biomass resource utilization have been one of the most important issues for biomass energy development. Besides being considered as a renewable resource, the utilization of crop residues shows a significant potential CO_2 emission reduction compared with the conventional fossil sources of energy production [58–60]. The utilization of residues for energy production could cause higher impacts for potential human toxicity, due to the ashes produced in the life-cycle processes of crop residues utilization [61]. Optimization of the stage of crop collection and transport can decrease the impacts of the energy use of crop residues.

It is well established that global warming potential is the greatest environmental challenge to energy development and therefore one of the most researched themes [62,63]. Utilizing crop residues for energy production can avoid potential GHG emissions from both direct and indirect land-use change [64,65]. The analysis indicate that the use of crop residue does not always have a carbon-negative result in all the scenarios, due to the low efficiency of the collection and high energy consumption during the conversion process. To have more environmentally friendly biofuel and bioelectricity products, more studies need to be conducted on, besides climate change, other impact occurred during the life stages of biofuels and bioelectricity production.

3.2 Life cycle cost result

Crop residues supply chain, including collection, transportation, pre-treatment, and conversion, takes a remarkable share of the total financial costs. The cost of biomass energy products is divided into two categories: the cost for the salary of the workers, and capital investment which includes capital equipment investment and operation of material cost, maintenance and disposing of cost. Due to the data availability, the salary and job creation during the construction of the conversion plant is calculated together with the capital investment cost in the study. The total employment from the life cycle of the scenarios varies depending on the conversion capacity of the plants. The functional unit is producing 1 MJ of energy.

The result obtained from the industry and site collection is summarized in Fig. 4. The total cost of energy application of crop residues ranges from US$ 12 to US$ 20 per 1 GJ energy project, which is equal to US$ 0.04 to US$ 0.07 per kWh energy produced. The lowest cost scenario is S1 of electricity production from combustion. In Scenario S1, the cost per GJ is US$ 12, of which 81% is owing to the capital investment (including equipment, material waste treatment, etc.) and the remaining less than 20% pertains the salary for workers (including on-site

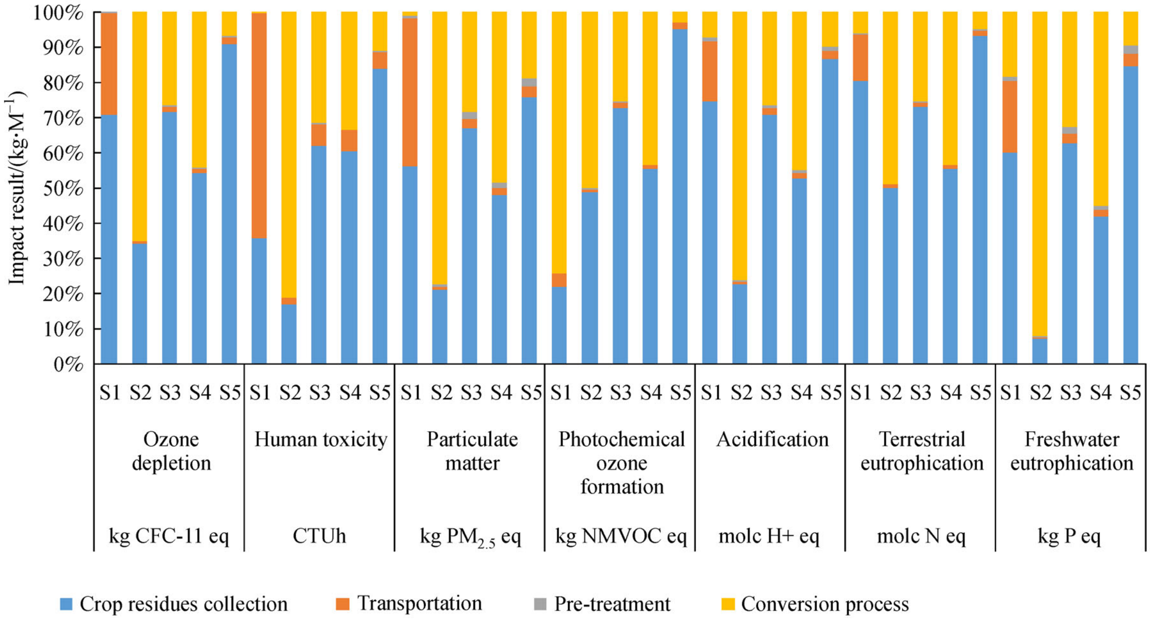

Fig. 3 Characterization results of five energy application scenarios of crop residues.

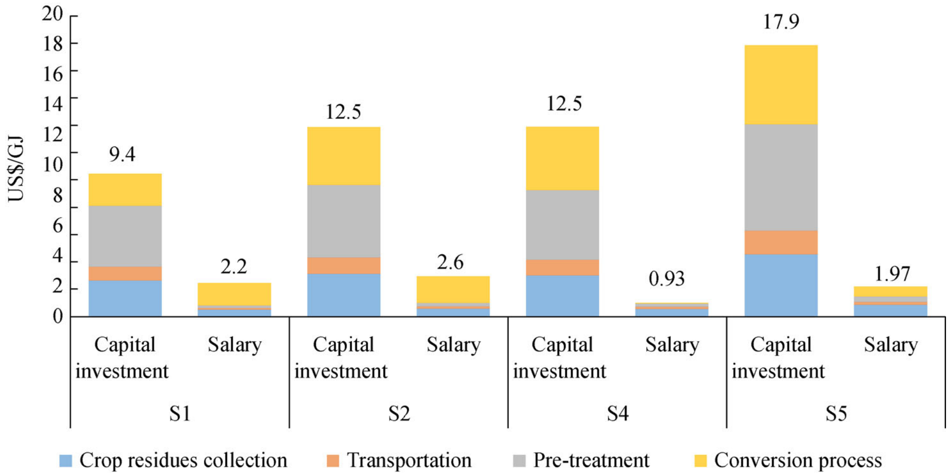

Fig. 4 Life cycle cost results of four energy application scenarios of crop residues.

labor cost of residues collection and transport, and workers on the sites of the plats, etc.). In Scenario S2, the total cost per GJ energy produced is $15, and the cost allocation is similar to that of S1, in which around 80% of the cost is the capital investment. In Scenarios S4 and S5, the total cost is US$ 14 and US$ 20 respectively, of which more than 90% of the total cost is realted to the capital investment, and less than 10% is for salary.

In this paper, the hotspot of energy utilization is identified as the pre-treatment process, which includes the pre-treatment of crop residues and storage afterward. First, pre-treatment requires energy input to dehydrate crop residues. Secondly, the process requires a large area for crop residue storage until they are transported to the conversion plant. The cost of biomass resources can highly depend on the transportation and local price of land, electricity, and workers. Nishiguchi and Tabata[66], who claimed that the collection and transportation of woody biomass is the bottleneck of the biomass utilization, which is due to the mountainous areas in Japan, also made this observation.

3.3 Social life cycle impact result

The social performance of energy applications of crop residues with regard to the different processes is outlined in Table 3. Because there is neither a complete nor a robust social assessment on the residues energy application, the

Table 3 Social life cycle impact results of energy application of crop residues

Impact category	Crop residues collection	Transportation	Pre-treatment	Conversion process
Workers				
Freedom of association	Non-existent: labor contracts are missing	Non-existent: labor contracts are missing	Existent	Existent
Working hours	8–12 h/d	8–12 h/d	~ 8 h/d	~ 8 h/d
Fair salary	Non-existent: wages are low	Non-existent: wages are low	Existent, based on contact	Existent, based on contact
Physical working condition	Non-existent: labor contracts are missing	Non-existent: labor contracts are missing	Standard, based on contract	Standard, based on contract
Health and safety	At low risk	At low risk	At low risk	At low risk
Social benefit	Not provided	Not provided	Provided	Provided
Local community				
Local employment	Promoted	Promoted	Promoted	Promoted
Society				
Contribution to economic development	Existent	Existent	Existent	Existent
Sustainable development	Existent	Non existent	Non-existent	High
Quality, safety and environmental standards	High	High	Medium	High

primary for this case is to interpret cautiously social results. The results are summarized in Table 3 and briefly described, refraining from providing clear conclusions or recommendations regarding the social performance.

For the S-LCA analysis, the results present social impacts being contributed by workers, local communities, and society in the four life cycle stages of crop residues applications. The results are obtained from the life cycle stages of the energy use of crop residues. The positive results are mainly caused by the application of a set of management, on-site activities, and the inclusion of environmentally friendly production activities. The relevant stakeholders generally benefit from the involvement of effective management and environmentally friendly on-site activities, where effects such as noise, dust, and other pollutants, can be significantly reduced. In this paper, working conditions from crop residues collection are identified as the hotspot of social impacts. The impact category of workers mostly pertains to farmers from local regions conducting the collection activities. They often work more than 8 h per day receiving a daily payment from US$5.7 to US$11.4 depending on local living conditions. The workers are normally paid daily without a specific contract, no social benefits or other guarantees of income. Among hot issues of the social impacts, safe and healthy living conditions are of top priority. A detailed investigation inidicate that there is a lack of health and safety regulation in the whole life cycle of process. Unlike the farmers working on the crop collection, the worker in pre-treatment plants and conversion plants has a positive impact due to the employment contract, which secures the working conditions and social benefits. The positive social impacts also apply to the other two impact categories of the local community and society. The energy utilization of crop residue creates job opportunities and increases the income of the farmers and the local community.

Renewable energy technologies provide a solid foundation for promotion of a clean energy generation and hence a more sustainable living environment. The environmental impact from the life cycle stage of crop residues energy applications is mainly caused by the crop residues collection and conversion stages. In the crops residue collection stage, low-efficiency harvesting machines and transport vehicles are used. The positive social impact is greatly affected by employment regulation while the workers from crop residue supplication and collection stages have a relatively poor social performance. It shows that improvement should be made on the crop residues collection and transport stage in both environmental and social aspects in order to achieve sustainable energy use of crop residues.

The reasons for the different results of social impact are the fact that social benefits were not presented locally and the negative impacts of biomass supply chains and power plants on the local environment were not properly understood and mitigated to local communities. Social benefit is an important part of the sustainable development of biomass energy. It is important that the social benefit of biomass energy development is not perceived locally, especially by the local workers, however, the negative impacts during the life cycle stage of biomass energy affect the local environments and the society. Compared with the people in cities, people in rural areas are often live in poverty. Therefore, one of the main challenges facing the Chinese government is to reduce the growing inequality between them. The sustainable development requires a balance between national concerns and local communities [67].

Farming in China is still based on household scale farming. The Chinese agricultural farming is likely to remain small-scale for some time in the future. The crop residue collection system is highly dependent on the motivation of the farmers, which is driven by economic factors [68]. Besides economic factors, the working conditions and social awareness need to be addressed, as farmers constitute a larger part of the national population who need more social caring due to low competitiveness in the labor market.

3.4 Discussion

This paper includes five scenarios for the life cycle stages of biomass from crop residues collection to replacing conventional energy sources. From the perspective of E-LCA, the five scenarios present environmental benefits to varying degrees compared with the conventional energy sources. For producing electricity, S2 is better than S1 as all environmental impact indicators of the former are much less than those in the latter. For producing fuels, all environmental impact indicators except human toxicity are S4, S5, and S3 from large to small while the order for human toxicity is S5, S4, and S3. This means S3 has the greatest environmental advantages in the three scenarios. From the perspective of LCC, S2 has more costs for both capital investment and salary than S1, and the same is true for S5 and S4. In addition, the implementation of the five scenarios could provide job opportunities and corresponding income for the farmers with the possible health and safety risks. Whatever, it is good for social development but the usefulness of the five scenarios are difficult to quantify due to the limitation of the method. In total, the choice of S1 and S2 mainly depends on the trade-off between environment and economy. Although S3, S4, and S5 have different environmental and economic performances, these alternative scenarios are likely to be developed together rather than a single option due to the lack of oil in China. Besides these five scenarios, Zhang et al. [69] compared the environmental performance of processing straw to fuels for substituting bulk coal and straw returning to field, and found that the former is far superior to the latter in reducing fossil energy consumption, greenhouse gas and pollutant emissions. Considering

China’s large consumption of bulk coal and serious pollution produced by it, making full use of biomass to produce fuels and electricity may be an effective way to improve the environment.

It is worth noting that the impacts on the soil by removing residues and other potential residues application were excluded in this paper. It has been clarified that energy production from crop residues can reduce soil carbon content with increasing CO_2 emissions into the atmosphere [70]. In many parts of the China, residues are placed in agricultural fields after grain harvest. Besides, crop residues, especially straw from small grains can also be harvested, stored and used for livestock bedding during the winter [45]. The exclusion of upstream stages cause no completed assessment results and may lead to inappropriate decisions for policymakers. Databases are used for most of the materials and transportation calculations, as very limited local data are available. The use of general rather than specific data in the assessment increases the uncertainty of the analysis concerning the specific case, and should, therefore, be seen as aiming at extrapolating a more general perspective from the specific case study. Therefore, building a local LCA database for materials and other relevant processes, to permit more specific assessments, is strongly encouraged.

Pertaining to the social impact assessment, the uncertainty of the result would be even high due to the high influence in local contexts. There is no completed methodology currently available for modeling S-LCA. Based on the current method, only certain aspects of social impacts can be assessed [56]. Regarding social impact results, for the particular case of biomass energy utilization, many of the methodological challenges of S-LCA still exist (functional unit, system boundary, indicators, source of data, etc.). The principle foundation of all life cycle methodologies is to do quantitative assessments. The quantitative social assessment must be compensated by qualitative and semiquantitative indicators when quantified data cannot be collected. Even though many things can be argued and improved in the future, the knowledge gap of S-LCA can never be closed [71]. In recent years, several issues related to social conditions in the production and manufacturing plants, such as working conditions in factories in China, have attracted the attention of the media at home and abroad.

4 Conclusions, recommendation and further research

Comprehensive analyses of environmental, economic, and social aspects were conducted using the three assessment tools in the life cycle management family (E-LCA, LCC, S-LCA). The life cycle methodologies are beneficial for a comprehensive understanding of biomass energy production and the trade-off between environmental, social, and economic values. This is important for decision making by public authorities and business developers. This paper covered crop residues collection, transportation, pre-treatment, and conversion technology. Five scenarios were developed and compared based on different energy products, which were bioelectricity, hydrogen, biomethanol, and bioethanol. It was found that the crop residue collection stage contributed the most to environmental impacts, and pre-treatment contributed more to the costs due to the costs of land occupation and energy input. The social impact is positive to local communities and the society. However, it is negative to on-site workers due to a lack of social services.

As raw materials, crop residues used for energy production were encouraged by the requirements for secure energy supply, fossil CO_2 emission reduction, and rural areas revitalization. Crop residues shows greater potentials in CO_2 emission reduction compared with fossil-derived products and services. In contradiction to the potential CO_2 emission reduction, the impacts of photochemical ozone formation, acidification and terrestrial eutrophication caused by crop residues are higher than those from fossil fuels. The other potential impacts besides climate change should be taken into consideration when developing the energy applications of crop residues. This paper identifies that workers in local communities are at the greatest risk of negative social impact. Social benefits/social security, working hours, and freedom of association are important issues to local farmers.

The Chinese government has recently announced a strategy to create bioethanol for transport fuel in 2020, which claims that no food supply would be affected [32]. One potential opportunity to contribute to bioethanol production and reduce intensity of land occupation is to apply biofuel production by utilizing resources and wastes from agricultural activity. The cradle to grave approach is a useful complement to assessment of cost, social, and environmental issues, which are all necessary considerations when making decisions about the future of bioenergy development in China. In practice, the reginal diffrences and the national policy should be considered, so that the weights to balance the three assessments should be decided by the specified region when making decisions.

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