Environmental Comparison of Straw Applications Based on a Life Cycle Assessment Model and Emergy Evaluation

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Straw is considered to be a renewable resource for bioenergy and biomaterial. However, about 70% of straw is burned in fields, which causes serious air pollution in China. In this study, a life cycle assessment (LCA) model, together with emergy evaluation, was built to compare four straw applications after harvest *vs.* direct burning, including bioethanol (BE), combined heat and power plant (CHP), corrugated base paper (CP), and medium-density fiberboard (MDF). The results showed that BE and MDF would avoid greenhouse gas (GHG) emissions by 82% and 36%, respectively, while CHP and CP would emit 57% and 152% more GHG , respectively, compared with direct straw burning. Bioethanol had the highest renewability indicator (*RI*) of 47.7%, and MDF obtained the greatest profit of 657 Yuan·bale^{-1}. The applications CHP and CP had low *RI* (< 10.3%) and profit (< 180 Yuan·bale^{-1}). Due to water recycling and electrical power as a coproduct, BE had the lowest value (3×10^{11} *sej*·Yuan^{-1}) of *EmPM* (emergy per unit money profit); the *EmPM* value of CP was 18.6 times higher than that of BE. The four straw applications would also greatly reduce particles emission (57 to 98%) to air. BE was judged to be the most environmentally friendly application among the four straw applications. Imposing a carbon tax would encourage investment in BE, but discourage the applications CHP and CP.

Keywords: Straw application; Life cycle assessment (LCA); Emergy evaluation; Bioethanol; Greenhouse gas emission

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INTRODUCTION

Crop residue is considered to be the most abundant renewable resource for bioenergy and biomaterials. There are an estimated 1549 Tg (73.9 Tg from available crop residues) annually available worldwide (Kim and Dale 2004). Jiangsu province is one of the most populated and developed provinces in China, and the yield of total crop residues was about 40 Tg annually (Gao 2010) to include straw from corn (*Zea mays* L.), cotton (*Gossypium hirsutum*), rapeseed (*Brassica napus*), rice (*Oryza sativa*), and wheat (*Triticum aestivum*). The conventional treatment of crop residues is open-field burning after grain harvesting to facilitate quick clearing of the land for the next season of planting. The high temperature of a fire may also control diseases and pests in subsequent crops. However, directly burning of crop residue adversely affects air quality in terms of $PM_{2.5}$, PM_{10} (particles with diameters less than 2.5 and 10 μm, respectively), and greenhouse gas (GHG) emission. The gases from burning straw have significant concentrations (5.26 mg/kg) of polycyclic aromatic hydrocarbons (Zhang *et al.* 2011), a group of carcinogenic compounds that impacts sensitive population health. Therefore, as an alternative to open-field burning, the sustainable application of crop residue is important for human health, environmental protection, and energy supply in Jiangsu province.

Crop residue is considered to be a second-generation bioethanol feedstock, which generally contains 25 to 46% cellulose, 12 to 31% hemicellulose, and 7 to 19% lignin (Naik *et al.* 2010; Gao *et al.* 2011). Developed pretreatment processes, such as dilute acid pretreatment (del Campo *et al.* 2006) and ammonia fiber expansion (Lau and Dale 2009), can decrystallize the lignocellulose structure and increase lignocellulase accessibility to hydrolysis of the cellulose and hemicelluloses, which can be fermented into bioethanol. For instance, 11 to 18% of dry corn stover (Gao *et al.* 2011) can be converted to bioethanol, most of which were from glucan and xylan in cellulose and hemicellulose. Cellulosic biofuel is very promising, having a low environmental impact and high reduction of GHG without raising food prices.

There are other products of crop residue, including electricity power supply and paper and fiberboard production. Straw has a high energy content; for instance, the lower heating values (LHVs) of corn stover and other herbaceous biomass (such as switchgrass) are 16.37 and 17.21 MJ/kg, respectively, which are about 72% and 76% of the LHV value for wet coal (Wang 2001, 2010). To be compatible with existing combustion equipment, crop residues are pelletized or gasified to produce electricity or heat, and the thermal efficiency is around 20 to 45% (Huang *et al.* 2008). The obstacles preventing the commercial practice of straw electricity generation are high construction costs and unstable feedstock supply (Zhang and Zhou, 2010). To make sustainable reusable paper, crop residue can be pulped with the addition of NaOH solution and Na_2S at an elevated temperature and pressure (Yoon *et al*. 2001). Wastewater treatment is necessary for black liquor emitted from the pulping process because of its high pH and content of malodorous reduced sulfur (Xiao 2005). Crop straw can also be used to replace timber in forests in the production of low-, medium-, and high-density fiberboards (Ye *et al*. 2007). Fiberboard can be used as insulation material and in furniture construction (Li *et al*., 2010).

Most research on crop residue applications has focused on conversion to bioethanol and electricity (Kim and Dale 2004; Cherubini and Ugiati 2010). A study by Kim and Dale (2004) found that 73.9 Tg of dried waste crop can produce up to 49.1 GL/yr of bioethanol. Although it has been argued that removing crop residue from fields can degrade soil quality, well-managed corn harvest strategies using manure, composite fertilizer, and winter cover can partially compensate the loss of soil quality (Fronning *et al.* 2008). The research of Steubing *et al.* (2011) showed that biomass conversion efficiency was the determining factor for the best use of biomass, and woody biomass was better for combined heat and power generation than non-woody biomass. However, non-woody biomass (such as crop residue) yielded comparative benefits when used for electrical power, bioethanol, or heat power (Steubing *et al.* 2011). There have been limited side-by-side studies comparing the advantages and disadvantages of the different crop residue applications that make paper, fibreboard, bioethanol, and electricity power. One major reason for the limited research comparing the overall impacts of these applications is that the products and their intermediates exist in various units as energy, mass, volume, and currency.

A life cycle assessment (LCA) can be used to calculate a product's energy efficiency, and total GHG balance by building an integrated framework of processes (European Commission, 2010; ISO, 2006a; ISO, 2006b), but it excludes the embodied energy from supporting systems (*e.g.*, "freely available" resources and the formation of these resources) (Rugani and Benetto 2012; Raugei *et al.* 2014).

To include natural resources, human services, and environmental effects of a product into system boundaries, emergy evaluation together with an LCA model has been proposed (Baral *et al.* 2012; Hossaini and Hewage 2012). Emergy of a product is defined as the embodied energy in the product, including the amount of total energy used in the whole supply chain of production or the memory of the (solar) energy that has been used in the supporting systems in the past (Odum 1996). The unit of emergy is typically the solar emjoule, which can be used to aggregate all the different flows of material, energy, information, and service. The conversion factor called transformity or unit energy value (UEV) is defined as the emergy required to make one unit of a given product or service (Odum 1996). Indices such as the renewability indicator (*RI*) (Hau and Bakshi 2004), potential greenhouse gas emissions ($GHG_{emitted}$) (Baral and Bakshi 2010), and emergy *per* unit money (*EmPM*) (Brown and Ulgiati 2004), can be used to assess the best use of straw for society and the environment.

Rice and wheat are the two most widely grown crops in Jiangsu province, China. Rice is sown in June and harvested at the end of October, and wheat is sown after rice and harvested in the spring. The total arable areas of these two crops were 2125.3 and 2189.5 kha, respectively, in 2009, corresponding to approximately 45% of the total arable area of Jiangsu province (4688 kha). The objectives of this study were first to build a gate-to-gate LCA model to assess four straw applications in avoided GHG emission, particle emission to air and nonrenewable resources usage, and then use emergy evaluation method to compare their environmental sustainability, which could be used to develop a sustainable energy and environmental strategies to recycle biomass waste.

EXPERIMENTAL

Materials

The major crops in Jiangsu are rice, wheat, rapeseed, corn, soybean, cotton, and barley. Their respective arable areas have remained fairly constant for the past 20 years (Zhang and Fan 2010). In this study, the yields of two major crops, rice and wheat, were surveyed in 13 counties of Jiangsu province using the *Statistical Yearbook of Jiangsu 2010* (Zhang and Fan 2010), which provided provincial agriculture statistics from 2009. The yields of rice and wheat were 23.2 and 12.4 Tg in 2009. The largest wheat-planting county is Xuzhou (320 kha), with a total wheat yield of 1.9 Tg. The largest rice-planting county is Yancheng (347 kha), where the total rice yield was 3.1 Tg.

Based on nine-year field data from the Changshu Ecology Center (Yan *et al.* 2010) located in Jiangsu province, the grain-to-straw ratios of rice and wheat were assumed to be 1.0. From the research of Liu *et al.* (2011), 70% of total rice straw yield and 68% of total wheat straw yield is directly burned in fields or burned at home as energy for cooking. The total burned rice and wheat straw in Jiangsu province amounts to 16.2 and 8.4 Tg annually. In this study, only burned straw was assumed to be potentially used for straw applications.

Methods

System description and Em-LCA boundary conditions

Because this study was concerned only with the potential directly burned straw, farming activities such as planting, tilling, and fertilizing were not considered in the model analysis. Five scenarios of a LCA model were created with the software of Gabi 6.0 (PE International; Stuttgart, Germany) (Volz and Volz 2013), using the libraryEcoInvent database 2.0 (Frischknecht and Jungbluth 2011), including the reference scenario of directly burning and four application scenarios (bioethanol biorefinery (BE), combined heat and power generation plant (CHP), corrugated base paper (CP), and medium density fiberboard (MDF)). In general, the four application scenarios (Fig. 1) involved processes from straw harvesting to bale, transporting to plant, chopping to chips, application processes, and wastewater treatment processes. In scenario BE, water and co-product electricity were recycled; in scenario CHP, heat was the co-product; and in scenario CP, organic fertilizer was the co-product. It was assumed that the four applications occurred at the same locations and the parameters in straw harvesting, transporting, and chopping to chips were the same in the four application scenarios. With reference to Gabi 6.0 and EcoInvent 2.0, a round bale with a weight of 700 kg was selected for the process of harvesting to bale, and a tractor was used to harvest and load bales. The round-trip transport distance from field to application plant was set at 50 km. Detailed process information can be found in Table 1. Because there was little information about the processes parameters from China, the general parameters from Europe (RER) or parameters from Switzerland (CH) were selected, and the parameters of electricity from China were selected as they were in EcoInvent 2.0 database.

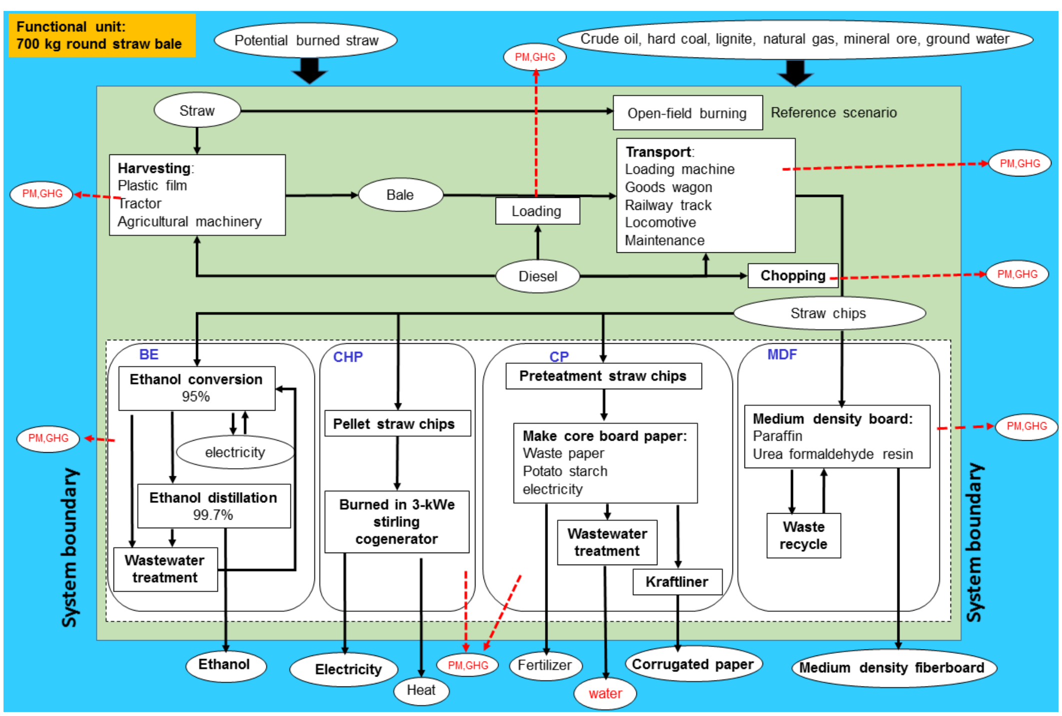

Fig. 1. System boundaries of this study. There were five scenarios, including a reference scenario of open-field straw burning, and four application scenarios (bioethanol (BE), combined heat and power plant (CHP), corrugated base paper (CP), and medium density fiberboard (MDF)).

Table 1. Selected Processes from EcoInvent 2.0 Used in this Study[a]

Processes	Processes in Ecoinvent	Modified parameters	Location in EcoInvent
Straw baling	CH: Baling (u-so)[b]		Agricultural means of production/work processes
Loading bales	CH: Loading bales (u-so)	1 bale = 700 kg	
Transport, freight, rail	RER: Transport, freight, rail (u-so)[c]	50 km, a round trip	Transport systems/railway
Straw chopping	RER: Industrial residual wood chopping, stationary electric chopper, at plant (agg - LCI result)		Wooden materials/benefication
	RER: Wood chips, mixed, from industry, u = 40%, at plant (u-so)[d]	bulk density of wheat straw was 52.1 kg·m^{-3};[e] straw chips bulk density 120 kg·m^{-3} [f]	Wood energy/fuels
Crop residue pellet	RER: Wood pellets, u = 10%, at storehouse (u-so)	straw u=17.5%,10% rape oil added straw pellet density was 721 kg·m^{-3}; Transport, lorry > 16t, fleet average [street] was 18 tkm	
Straw chips for bioethanol	CH: Wood, in distillery (p-agg)[g]	1 kg 95% ethanol was 0.162 MJ electricity[h]	Biomass/fuels
	RER: Ethanol, 99.7% in H2O, from biomass, at distillation (u-so)		
Straw pellet for CHP processing	CH: Wood pellets, burned in stirling cogen unit 3kWe, future(p-agg)	energy efficiency 0.9, the ratio of heat to electricity was 3:1	Biomass/cogeneration
Straw chips for corrugated paper	RER: Corrugated board base paper, kraftliner, at plant (u-so)	for 1 kg corrugated board paper, the process would produce 0.33 kg organic fertilizer[i]	Paper and cardboard/cardboard and corrugated board
	RER: Core board, at plant (u-so)	1.5 kg straw chips and 0.33 kg waste paper to make 1 kg core board	Paper and cardboard/packaging papers
	RER: Kraft paper, unbleached, at plant (u-so)	0.58 kg straw chips for 1 kg kraft paper	
Straw chips for MDF[j]	RER: Medium density fibreboard, at plant (u-so)	density of MDF was 800 kg·m^{-3}; urea formaldehyde resin was 2%[k]	Wooden materials/benefication

[a]the processes were from GaBi 6.0 and EcoInvent 2.0 (Frischknecht and Jungbluth 2011; Volz and Volz 2013); [b]CH: Switzerland; u-so: a unit process, single operation; [c]RER: Europe; [d]u = 40% is 40% moisture; [e]Chevanan *et al.* 2010; [f]Tabil *et al.* 2011; [g]p-agg: partially aggregated process; [h]Laser *et al.* 2009; [i]Ke 2005; [j]MDF: medium density fiberboard application; [k]Zhou *et al.* 2003

Infrastructure and energy consumption to produce machines over their lifespan (30 years) were insignificant (Lardon *et al.* 2009), so their costs were not included in the profit calculation. The functional unit was one straw bale with 700 kg of dry biomass, and the products of the four application scenarios were ethanol and electricity, electricity and heat, corrugated base paper, and medium-density fiberboard (Fig. 1).

Estimated production of straw applications

There is no real industrial data concerning ethanol production from rice and wheat straws. Therefore, it can be estimated by straw sugar composition (Gao *et al.* 2011) using the following formula:

$$E_{prod} = 0.48 \times \text{glc} + 0.29 \times \text{xyl} \quad (1)$$

where E_{prod} (% kg/kg dry biomass) is ethanol production of dry biomass; and glc and xyl are converted glucan and xylan contents, which were assumed to be 90% and 65% of structural glucan and xylan contents in straw under optimum conditions (Table 2). The estimated ethanol production was 178.4 g/kg dry mass for rice straw and 193.3 g/kg dry mass for wheat straw. The value of wheat straw bioethanol production was consistent with the results reported by Zhong *et al.* (2009). However, the predicted values of ethanol production will prove to be overestimated when taking the complexity of a larger scale bioethanol biorefinery into consideration. In the scenario of straw bioethanol application, the modified process “CH: wood, in distillery (p-agg)” was selected for 95% ethanol production and the distance for transport biomass from chopping plant to biorefinery was 5 km (10 km round trip) with a 20 to 28 Mg truck. The 95% bioethanol was distilled to 99.7% with the process “RER: ethanol, 99.7% in H_2O, from biomass, at distillation (u-so)” (Table 1).

The lower heating values (LHV) of straw were assumed to be 13.07 MJ/kg for rice and 15.06 MJ/kg for wheat (Maung and McCarl 2008). Straw bales have to be chopped (density 120 kg/m^3) and pressed into pellets (density 721 kg/m^3) before the process of producing electricity. In this study, it was assumed that pellets from both rice straw and wheat straw had the same properties, and 10% rapeseed oil was added to aid combustion. The LHV value of straw pellets are 95480 MJ/m^3 for rice and 10858 MJ/m^3 for wheat, and the moisture level was 17.5% (Frischknecht and Jungbluth 2011). The technology used in CHP was a 3-kWe stirling cogenerator with combined heat and electricity power plant, and the energy efficiency was 0.9. Heat was the co-product, and the ratio of heat to electricity was 3:1 (MJ:MJ). The stirling cogenerator power unit is the most plausible future technology for biomass electricity because it can be used in a small-sized power plant and is suitable for use in Jiangsu province. Based on the conditions in Jiangsu, the processes used in straw CHP application were modified from those in Ecoinvent 2.0, including “RER: wood pellets, u = 10 %, at storehouse (u-so)” for straw pellet and “CH: wood pellets, burned in stirling cogen unit 3kWe, future (p-agg)” for the CHP process. The distance for transporting biomass from the chopping plant to the CHP plant was 5 km (10 km round trip) with a 20 to 28 Mg truck.

Corrugated paper is a widely used paper product for packaging that is lightweight, durable, and recyclable. In this study, corrugated board base paper was selected as one straw application, in which about 33% recycled paper is used. This property makes it sustainable for the purpose of this study. The co-product of this application was organic fertilizer; the ratio of co-product to product was 1:3. The production of corrugated board base paper (P_{prod}) was 1.125 kg/kg dry straw in the model. The process used to make core board paper was modified from the process "RER: core board, at plant (u-so)," the process to make kraft paper was modified from the process "RER: kraft paper, unbleached, at plant (u-so)," and the process to make corrugated board base paper was modified from the process "RER: corrugated board base paper, kraftliner, at plant (u-so)." The distance for transporting biomass from the chopping plant to the CHP plant was 5 km (10 km round trip) with a van < 3.5 Mg.

Straw can take the place of wood to make medium density fiberboard (MDF), which is a building material. The properties of straw MDF followed patent ZL01137361.X published in China (Zhou *et al.* 2003), so that the density of MDF was 800 $kg \cdot m^{-3}$, including 4% moisture and 2% glue (urea formaldehyde resin). Based on Zhou *et al.* (2003), the production of MDF was 1.33 m^3/Mg dry straw. The selected process for this application was "RER: medium density fibreboard, at plant (u-so)." The distance for transporting biomass from the chopping plant to the MDF plant was 5 km (10 km round trip) with a truck < 16 Mg.

Total production of one application for one county

The total amount of one application product ($P_{tot,ij}$) from one county can be calculated as,

$$P_{tot,ij} = \Sigma P_{ij} \times Y_i \times R_i \tag{2}$$

where $P_{tot,ij}$ is the *j*th product from *i*th crop residue (rice straw or wheat straw); *j* is bioethanol (BE), electricity from combined heat and power (CHP), corrugated board based paper (CP), or middle-density fiberboard (MDF) Y_i (Tg) is the total yield of *i*th crop residue of one county in Jiangsu province; and R_i (%) is the average ratio of *i*th crop residue used for direct combustion in the field and at home in Jiangsu from 2006 to 2008 (70% for rice straw and 68% for wheat) (Liu *et al.* 2011), which was assumed to be used for straw applications.

Particles and greenhouse gases emission

Particles emission of one straw application was obtained through the LCA model and compared with the reference scenario to calculate the percentage of reduced particles emission.

The greenhouse gas emission profile of each straw application ($GHG_{emitted}$) was first calculated in the LCA model and then characterized to indicate its global warming potential by using the CML2001 impact assessment method (Guinée *et al.* 2001). The $CO_{2,eq}$ factors of four major greenhouse gases CO_2, CO, CH_4, and N_2O) (Table 2) were 1, 1.9, 25, and 298, respectively (Forster *et al.* 2007; Liu *et al.* 2011). The application could avoid GHG emission when $GHG_{emitted}$ of one application was smaller than the GHG emission from the reference scenario (GHG_{burned}) at the same weight of straw bale.

To calculate total GHG emission GHG_{tot} (Tg $CO_{2,eq}$) from directly straw burning in one county in Jiangsu Province, Eq. 3 was used,

$$GHG_{tot} = \sum_{i=1}^{n} (Y_i \times GHG_{bumed,i} \times R_i) \tag{3}$$

where i is the type of straw (rice or wheat); Y_i (Tg) is the total yield of the i^{th} crop residue in one county; and R_i (%) is the average ratio of the i^{th} crop residue burned both in fields and at home in Jiangsu from 2006 to 2008 (Liu *et al.* 2011).

Table 2. Characteristics of Rice and Wheat Straws

	Rice	Wheat
Straw composition[a]		
Glucan (%)	34.7	36.9
Xylan (%)	15.1	18.0
Arabinan (%)	2.2	3.4
GHG emission factor from straw burning[b]		
CO_2 (kg / kg dry biomass) (1)	1.67	1.37
CO (kg / kg dry biomass) (1.9)	0.068	0.058
CH_4 (kg / kg dry biomass) (25)	0.002	0.002
N_2O (kg / kg dry biomass) (298)	0.00011	0.00005
$GHG_{emitted}$ (kg / kg dry biomass)	1.73	1.38
Particle matter (kg/kg dry mass)[c]	0.00628	0.00875

[a]The rice straw composition is from Gao (2010), and the wheat straw compostion is from Nigam (2001) and Salvachúa *et al.* (2011); [b] data were from Forster *et al.* (2007) and Liu *et al.* (2011); the numbers in parentheses were CO_2 equivalent factors; [c] data were from Cao *et al.* (2008).

Table 3. Prices, Units, Energy Contents, and UEVs of Input Resources

Resource	Price[a]	Energy content[b] (LHV)	UEV
Nonrenewable energy resources			
Crude oil	523.3 Yuan/barrel [c]	42.7 MJ/kg	9.07×10^4 *sej*/J [d]
Hard coal	569.4 Yuan/Mg [e]	28.6 MJ/kg (coking coal, wet)	6.69×10^4 *sej*/J [f]
Lignite	3000 Yuan/Mg [g]	26.1 MJ/kg (bituminous coal)	6.69×10^4 *sej*/J [f]
Natural gas	3.4 Yuan/m^3	47.1 MJ/kg	5.88×10^4 *sej*/J [f]
Nonrenewable elements			
Aluminum	15406 Yuan/Mg [h]		1.43×10^9 *sej*/g [f]
Copper	59177 Yuan/Mg [i]		1.61×10^8 *sej*/g [f]
Iron	3908 Yuan/Mg [j]		1.44×10^9 *sej*/g [f]
Water resource			
Ground water	0.0361 Yuan/Mg	Gibbs free energy 4940 MJ/kg	2.95×10^5 *sej*/g
Renewable energy resources			
Rice (Wheat) straw	250 Yuan/Mg	13.1 (15.1) MJ/kg	4.70×10^3 *sej*/J [k]

[a]Yuan is the Chinese currency and the exchange rate was 1 Yuan to 0.16 US dollar as quoted on May 25, 2013; [b]Wang 2001); [c]average value (CNGOLD 2012) of crude oil from 2007-2012; [d]Baral *et al.* 2012; [e]average value (Wong 2012) of 2013; [f]Jiang *et al.* 2008; [g]Wang 2010; [h]average value (SMM 2012) of aluminum price from 2007-2012; [i]average value (SHMET 2012) of copper price from 2008-2012; [j]average value (ZZ91 2011a) of cast iron from 2010-2012; [k]Xia and Qin 2009

Emergy evaluation for straw applications

The emergy flow chart was drawn as Fig. 2. Based on the LCA model, total emergy inputs (ΣEm_{input}, *sej*) of renewable and non-renewable resources and materials were calculated, estimated from the multiplication between the input amounts and their corresponding unit emergy values (UEVs) (Table 3). The products and co-products prices and UEVs are shown in Table 4.

Table 4. Prices, Units, Emergy Contents, and UEVs of Products and Coproducts

Product	Price	Energy content (LHV)	UEV
Ethanol	4500 Yuan/Mg [a]	27.0 MJ/kg [b]	1.70×10^5 *sej*/J [c]
Gasoline	7.76 Yuan/L [d]	43.4 MJ/kg [b]	1.11×10^5 *sej*/J [e]
Electricity	0.792 Yuan/KWh		2.72×10^5 *sej*/J [f]
Heat	0.018 Yuan/MJ [g]		9.49×10^4 *sej*/J
Corrugated paper	1650 Yuan/Mg [j]		3.69×10^9 *sej*/g [h]
Organic fertilizer	260 Yuan/Mg		2.70×10^6 *sej*/g [i]
MDF	104 Yuan/2440×1220×18mm		1.87×10^9 *sej*/g
a carbon tax [c]	68.5 Yuan/Mg [k]		

[a]21food 2013; [b]Wang 2001; [c]Sciubba and Ulgiati 2005; [d]average price of regular gasoline No. 93 (EIA 2012) from 2007/01-2013/09; [e]Odum 1996; [f]Sha and Hurme 2012; [g]ZZ91 2011b; [h]Jiang *et al.* 2008; [i]Xia and Qin 2009; [j]price of corrugated paper from renewable resources (Haukoos 1995); [k]IETA 2012; the exchange rate was 1 Yuan to 0.16 US dollar as quoted on May 25, 2013.

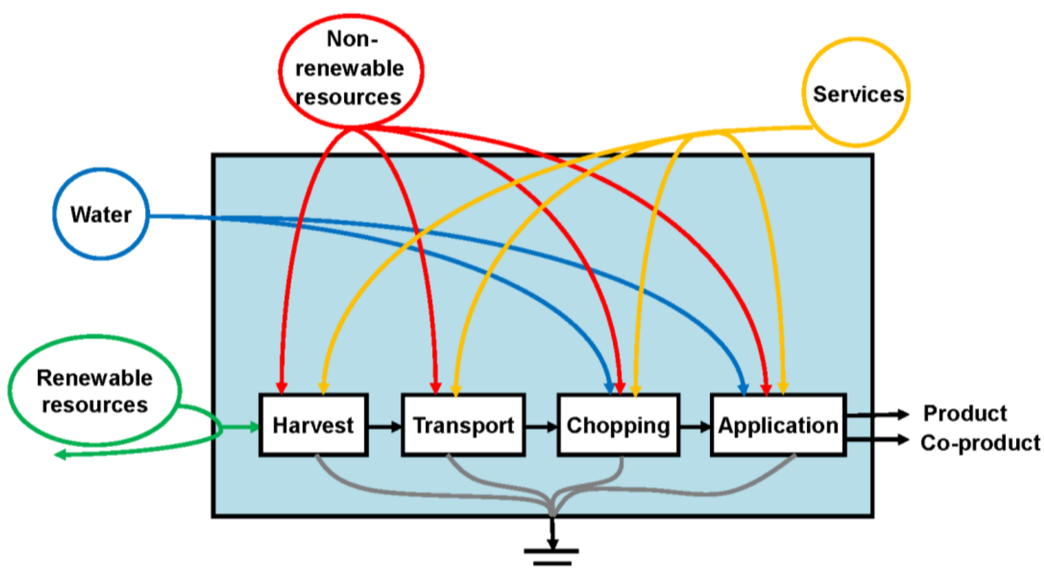

Fig. 2. Emergy flow chart in the study

Renewability indicator (*RI*, %) is defined as the input emergy ratio between renewable and total resources and materials (Baral *et al.* 2012), as given by Eq. 4,

$$RI(\%) = \frac{\Sigma Em_{\text{ren}}}{\Sigma Em_{input}} \times 100 \qquad (4)$$

where ΣEm_{ren} is the input emergy (*sej*) from renewable resources and materials. The renewable resource in this study was straw. Water is a limited resource in China, so it was not treated as a renewable resource. Because only potential burned straws were considered in the study, soil organic matter was not included as a nonrenewable resource in this study. A higher *RI* value denotes a more sustainable application.

Emergy per unit money

The profit of a 700 kg round straw bale with one application was calculated based on the cost of input resources and materials ΣP_{input} (Yuan), products, and coproducts ΣP_{prod} (Yuan). Because labor is relative cheap in China, 15% of the total profit was considered as a labor fee in the study and would be abstracted from the total profit. To reduce GHG emission worldwide, a carbon tax was proposed for GHG exchange market that could influence industrial practice. The amount of sequestrated CO_2 by crops could be exchanged via a carbon tax (IETA 2012) to make a profit. In this study, a carbon tax of 0, 69, and 137 Yuan/Mg (0, 11, 22 US dollar/Mg) was assumed to illustrate the influence of this policy on straw application. The index of emergy *per* unit money (*EmPM*, *sej*/Yuan) can be calculated using Eq. 5:

$$EmPM = \frac{\Sigma Em_{input}}{\Sigma P_{\text{prod}} - \Sigma P_{\text{input}}} \qquad (5)$$

This index helps compare applications' effects on the environment and economy by normalizing products and coproducts into a common unit. The higher value of *EmPM* means that more emergy is required to generate one unit money (Yuan) of profit, which is less friendly to the environment compared to a lower value. The exchange rate for the Yuan, as quoted on May 25, 2013, is assumed to be 1 Yuan to 0.16 US dollar.

Sensitivity analysis

A sensitivity analysis of Em-LCA was conducted to investigate the effects of the parameters used in the model on nonrenewable energy resources input and GHG emission output, including bale density, transport distances from farm to application plant, and production of one application. The range of the variable parameters was set at ± 30%. A Monte Carlo simulation of a Gaussian distribution was also performed (n = 1000) to test profit sensitivity of one application to sale prices of resources, materials, and products in each scenario. The degree of sensitivity of the application profit S_{ij} was calculated based on Eq. 6,

$$S_{ij} = \frac{\Delta I_i}{\Delta P_j} \qquad (6)$$

where ΔI_i (%) is the change range of the ith application profit due to the j^{th} parameter price change range ΔP_j (± 30%).

RESULTS AND DISCUSSION

Particles and GHG Emission from Straw Burning

From previous research (Table 2) of Cao *et al.* (2008), a bale of rice straw would emit 4.40 kg particles and a bale of wheat straw would release 6.13 kg particles. All the four applications would reduce particles emission based on the LCA model, in which 98%, 76%, 57%, or 82% particles would be reduced with rice straw application of BE, CHP, CP or MDF, respectively. The results indicated that straw applications were helpful in relieving China's serious air smog pollution.

Based on the estimation that 70% of the rice straw and 68% of the wheat straw were burned both in fields and at home, the total GHG emission from burning rice and wheat straw in Jiangsu in 2009 were 37.4 Tg $CO_{2,\ eq}$ (Fig. 3). The calculations indicated that Yancheng was the county with the most GHG emissions (5.94 Tg $CO_{2,\ eq}$) from burning rice and wheat straw, while Wuxi emitted the least GHG (0.98 Tg $CO_{2,\ eq}$) in proportion to arable areas and yields.

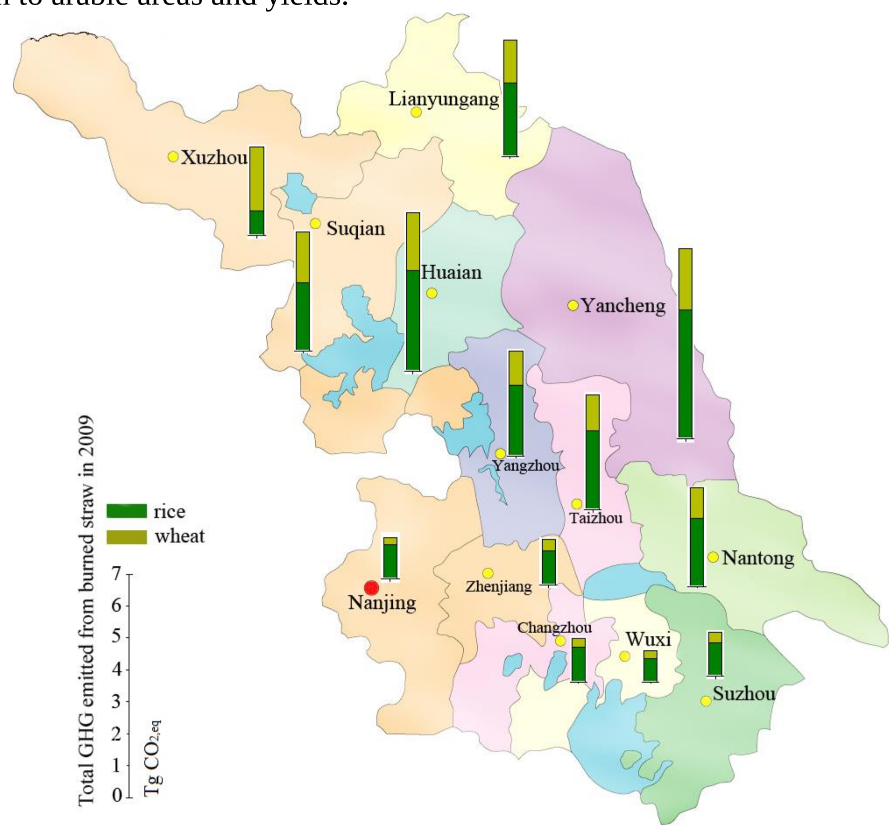

Fig. 3. Total predicted GHG emission from directly burned rice and wheat straws in 2009, Jiangsu province. The image is a map of Jiangsu, and each county has its own color with total predicted GHG emission bar. The scale in unit Tg $CO_{2,eq}$ and color legend are shown in the bottom left-hand corner of the figure

Based on calculations, the total burned straw in 2009 in Jiangsu province had the potential to produce 7164 ML of bioethanol, which could replace 4442 ML of gasoline if 1 L of ethanol has the same energy value as 0.62 L of gasoline (Farrell *et al.* 2006) or produce 38,128 GWh of electricity, which is about 11.5% of the total consumed electricity in Jiangsu in 2009 (Zhang and Fan 2010). It could also produce 20.4 Tg of corrugated base paper, which could save 54.2 Mm^3 of softwood and 11.2 Mm^3 of hardwood (Frischknocht and Jungbluth 2007), or produce 40.8 Mm^3 of MDF, which could save 58.5 Mm^3 of softwood and 19.5 Mm^3 of hardwood (Frischknocht and Jungbluth 2007).

GHG Emissions from Straw Applications

For the reference scenario of direct straw burning, the value of GHG_{burned} was 1210 kg of $CO_{2,eq}$ *per* bale for rice straw and 964 kg of $CO_{2,eq}$ *per* bale for wheat straw. Straw application could partially avoid GHG emission from straw burning. Based on calculation through the LCA model in this study, the processes in CP scenario emitted the most GHG (3055 kg $CO_{2,eq}$), followed by CHP (1904 kg $CO_{2,eq}$) among the four application scenarios of rice straw. The GHG emissions from the processes in BE and MDF applications were 215 and 771 kg of $CO_{2,eq}$, respectively. Thus, applications of BE and MDF could avoid GHG emission by 82% and 36%, while applications of CHP and CP would emit 57% and 152% more GHG compared with direct straw burning. These results indicated that BE and MDF were more environmentally friendly than CHP and CP applications. Similar results were obtained for wheat straw applications.

The results of the simplified profit calculation (Fig. 4) show that MDF application had the greatest profit, 657 Yuan *per* bale for both rice and wheat straw, with the assumption that rice and wheat straw have the same properties in MDF. The BE obtained greater profit (251 Yuan *per* bale for rice straw, 286 Yuan *per* bale for wheat straw) than CHP and CP applications (162 to 221 Yuan *per* bale). Because crop could sequester carbon from atmosphere, the avoided biogenic GHG emissions from crop residue applications would be considered as negative values.

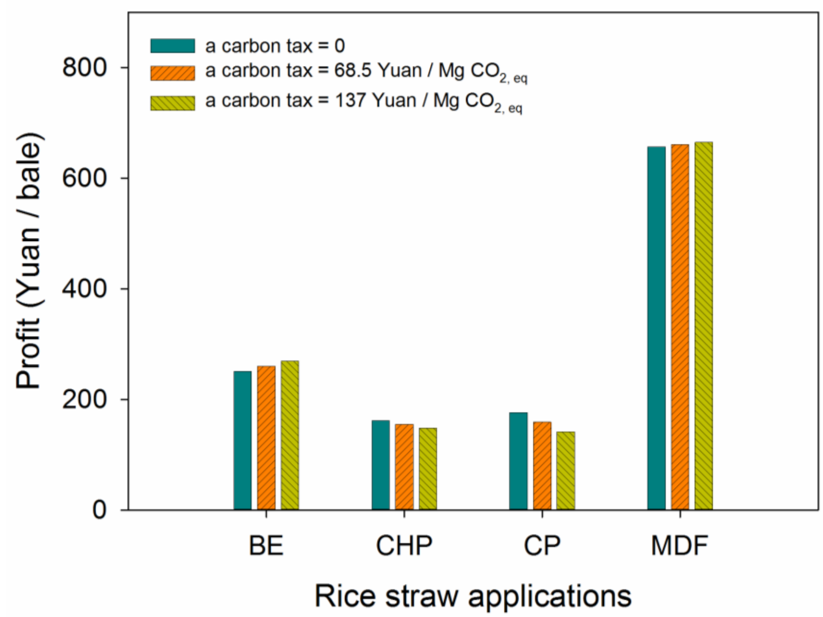

Fig. 4. A carbon tax effects on the profits of rice straw applications *per* bale; BE: straw application for bioethanol; CHP: straw application for combined heat and power plant; CP: straw application for corrugated base paper; MDF: straw application for medium density fiberboard. A bale has a weight of 700 kg of dry biomass

As suggested in the Copenhagen Climate Convention of 2009, a carbon tax in the GHG exchange market would be helpful in cutting global GHG emissions. If the carbon tax of 68.5 Yuan/Mg was included in the profit calculation, then BE and MDF would have 3.7% and 0.6% more profit, while CHP and CP would have 4.0% and 9.8% less profit; if the carbon tax were increased to 137 Yuan/Mg, the profits of BE and MDF would increase to 270 and 665 Yuan per bale. The results (Fig. 4) indicate that regulating the carbon tax would stimulate more investment flow to straw BE application, would have a relatively minimal effect on MDF application, and would discourage investment in CHP and CP applications.

Emergy Analysis

Emergy uses the solar emjoule (*sej*) to account for emergy flows in the Em-LCA model, which overcomes the difficulty in comparing various units of different products, services, human labor, and environmental effects (Brown and Ulgiati 2004). The emergy input values of resources and materials can be found in Tables 5. The CHP and CP applications had higher values of ΣEm_{input} than the other two applications.

Table 5. Input Emergy (*sej*) of Four Rice Straw Applications *per* Bale with 700 kg of Dried Straw[a]

Flow	BE	CHP	CP	MDF
Nonrenewable energy resources				
Crude oil	2.30×10^{13}	1.14×10^{14}	2.51×10^{14}	4.55×10^{13}
Hard coal	2.94×10^{12}	2.32×10^{14}	6.46×10^{14}	3.03×10^{14}
Lignite	2.49×10^{12}	1.13×10^{13}	3.11×10^{13}	9.00×10^{12}
Natural gas	1.38×10^{13}	2.87×10^{13}	1.20×10^{14}	1.34×10^{14}
Nonrenewable elements				
Aluminum	2.46×10^{10}	2.75×10^{11}	2.00×10^{12}	1.06×10^{12}
Copper	2.28×10^{9}	1.53×10^{10}	2.58×10^{10}	9.15×10^{9}
Iron	1.01×10^{12}	9.95×10^{12}	6.56×10^{12}	3.42×10^{12}
Water resource				
Water [b]	4.63×10^{11}	3.05×10^{12}	2.47×10^{13}	3.81×10^{12}
Renewable energy resources				
Rice straw	4.30×10^{13}	4.30×10^{13}	4.30×10^{13}	4.30×10^{13}
Total emergy input	9.01×10^{13}	4.64×10^{14}	1.18×10^{15}	5.56×10^{14}
RI[c] (%)	47.7	9.26	3.64	7.73
EmPM (10^{11} × sej/Yuan)	3.05	24.4	56.9	7.20

[a]Four straw applications with a bale of 700 kg dried straw as the functional unit, BE for bioethanol application, CHP for combined heat and power plant application, CP for corrugated base paper application, MDF for medium density fiberboard application; [b]because water is a limited resource in China and its recycling was longer than straw applications, it was not considered a renewable resource; [c]renewability indicator *RI* (%) = $\Sigma Em_{\text{ren}} / \Sigma Em_{\text{input}} \times 100$, where ΣEm_{ren} (*sej*) and ΣEm_{input} (*sej*) were input emergy of the renewable resources and total input emergy of renewable and nonrenewable resources, including energy resources, elements, materials

The results showed that BE application had the highest *RI* (47.7% for rice straw and 50.0% for wheat straw) among the four applications. The *RI* values of CHP and MDF applications were in the range of 7.73% to 10.3%, and the CP application had the lowest *RI* value (3.64% for rice straw and 4.17% for wheat straw). The higher *RI* of BE was due to water and partial co-product electricity, which could be reused during biorefinery processing; the lowest *RI* of CP application might result from greater electricity and water usage during paper production. The BE application was the most sustainable straw application among the four applications.

The values of *EmPM* for the four rice straw applications were in the range of 3.05 to 56.9 × 10^{11} *sej*/Yuan (Table 5), which could be converted to 1.9 to 35.4 × 10^{12} *sej*/dollar. The application of CP had the highest *EmPM*, which was 18.6 times greater than BE application. This result indicated that CP in Jiangsu was not an environmentally favorable application when compared with the other applications.

Sensitivity Analysis

The results of a sensitivity analysis show that input flows of nonrenewable energy resources and output flows of GHG emissions in the LCA model were stable with the change values of bale density, transport distances from farm to plant, which were selected to test model stability. From a Monte Carlo simulation, the sale prices of products (BE, CHP, CP, and MDF) would greatly influence straw application profits, especially for CP application, in which the sensitivity was 8.72 when corrugated paper price varied by ± 30%. Because more resources and materials (ΣEm_{input} 1.18 × 10^{15} *sej*) were required (Tables 7 and 8), CP profit was the most unstable.

CONCLUSIONS

1. Based on the life cycle assessment (LCA) model, bioethanol and medium density fiberboard applications can save 995.3 and 439.1 kg $CO_{2,eq}$ of greenhouse gases (GHG) (rice straw), respectively, or 732.4 and 193.2 kg $CO_{2,eq}$ of GHG (wheat straw), respectively, per 700-kg bale. The bioethanol (BE) application had the highest *RI* (47.7%) among the four applications, while the other three applications were in the range of 5.74% to 11.0%.
2. These results showed that BE application was the most environmentally friendly application with the lowest emergy per unit money profit (*EmPM*) (1.52 × 10^{11} *sej*·$Yuan^{-1}$). The medium density fiberboard application had the greatest profit of 657 Yuan·$bale^{-1}$ (~$105 *per* bale), and the value of *EmPM* was 7.16 × 10^{11} *sej*·$Yuan^{-1}$. The combined heat and power application and corrugated paper application had a return on investment (*RI*) lower than 10%, and would emit 694 and 1844 kg $CO_{2,eq}$ of GHG (rice straw), respectively, or 1076.5 and 2090.4 kg $CO_{2,eq}$ of GHG (wheat straw), respectively, compared with direct straw burning, which indicated that these two applications were not environmentally favorable.
3. Through a carbon tax regulation, more investors would tend to choose bioethanol application rather than combined heat and power application and corrugated paper application, thus being able to make more profit.
4. The results of this study indicated that bioethanol and medium density fiberboard applications would be better straw applications than combined heat and electricity and corrugated paper applications in Jiangsu province, China at the current level of technology.

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