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Article

Emergy Evaluation of Different Straw Reuse Technologies in Northeast China

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Abstract: Open burning of straw in China has degraded agricultural environments and has become a contributor to air pollution. Development of efficient straw-reuse technologies not only can yield economic benefits but also can protect the environment and can provide greater benefit to society. Thus, the overall benefits of straw-reuse technologies must be considered when making regional development planning and enterprise technology decisions. In addition, agricultural areas in China cross several climatic zones and have different weather characteristics and cultural conditions. In the present study, we assessed five types of straw-reuse technologies (straw-biogas production, -briquetting, -based power generation, -gasification, and -bioethanol production), using emergy analysis, in northeast China. Within each type, five individual cases were investigated, and the highest-performing cases were used for comparison across technologies. Emergy indices for comprehensive benefits for each category, namely, EYR, ELR, and ESI were calculated. Calculated indices suggest that straw-briquetting and -biogas production are the most beneficial technologies in terms of economy, environmental impact, and sustainability compared to straw-based power generation, -gasification, and -bioethanol production technologies. These two technologies can thus be considered the most suitable for straw reuse in China.

Keywords: emergy; straw-reuse technology; comprehensive analysis; northeast China

1. Introduction

Biomass energy continues to receive global attention as an alternative to fossil fuels such as oil and coal. In China, straw is one of the main biomass waste products of agriculture, accounting for 18% of the total [1]. The main components of straw are cellulose and, to a lesser degree, hemicellulose and lignin, all of which represent valuable raw materials for industrial and agricultural production. However, about 50% of agricultural straw in China has been disposed of by open burning in recent years. Extensive use of this mode of disposal has resulted in increased emission of airborne pollutants such as carbon dioxide, carbon monoxides, nitrogen oxides, and benzene [2]. In 2014, 9.4×10^7 tons of agricultural straw that had been openly burned released 9.1×10^6 tons of CO and 1.1×10^8 tons of CO_2 [3,4]. Inappropriate straw disposal has thus become the focus of public and official attention in China.

Considering China's expected environmental challenges and its large demand for energy, increased biomass energy usage is likely to become a requisite for reversing these potentially destructive trends. The Chinese government has implemented a variety of policies to improve straw reuse technologies, such as biogas, direct combustion, straw briquetting, bioethanol production, and gasification [5,6]. Although developing straw-reuse technologies has been a priority since the 1980s and a number of straw-reuse demonstration projects have been completed in China, the future of these projects is currently not viewed with optimism. They have to contend with inadequate supply of straw, large required investments, and low economic benefits [7]. Thus far, most of the strategic decision methods used by straw-reuse projects compare economic and environmental benefits [8–11]. Some projects assess social benefits, the results for which are qualitative [9]. Emergy is the sum total energy of one type required directly or indirectly for the production of goods. Emergy analysis is suitable for evaluating economic and environmental benefit, as well as the sustainability of straw-reuse systems and could help identify appropriate modes of straw reuse. Emergy analysis has been applied to a variety of agro-ecosystems and agricultural biomass reuse industries, such as biogas systems [12,13] and "four-in-one" eco-agricultural systems [14] and agricultural development [15,16]. It has been applied to straw gasification [7] and direct combustion projects [17], agricultural circular economical models [18,19], ethanol production, cropping systems, and other agricultural industries. There are, however, few emergy studies comparing the comprehensive benefits of different types of technologies [17,20,21]. Determining the optimal implementation among the many types of straw reuse projects is an important goal of government and industries.

The objective of this study was to employ emergy analysis to comprehensively evaluate straw-reuse technologies in China. We assessed 25 projects, including examples of biogas production, straw-based power generation, straw briquetting, straw gasification, and bioethanol production. A study of the economic-environmental-social dimensions of straw-reuse engineering was performed by accounting for inputs from ecological, social, and economic systems, as well as outputs to the socioeconomic system. Emergy indices for net energy yield (emergy yield ratio, EYR), environmental loading (environmental loading ratio, ELR), and emergy sustainability (emergy sustainability index, ESI) were calculated to evaluate the economic and environmental benefits, as well as sustainability of individual cases.

2. Materials and Methods

2.1. Procedure for Emergy Evaluation

Five main steps were required for emergy evaluation of straw-reuse technologies. First, detailed diagrams of emergy systems of the technologies were completed, with the reuse and energy generation process included in the systems' boundary, but with the processes for straw collection, straw transport, and waste disposal excluded. Second, raw input and output data were collected together with appropriate emergy transformation factors, and a raw data table was created for each case (Tables S1–S6). Cases included renewable resources from natural ecological systems (R), non-renewable resources from natural ecological systems (N), non-renewable resources obtained from socioeconomic systems (F), and yield from straw reuse projects (Y). Third, raw data were converted to emergy data. Fourth, the different types of straw-reuse cases were quantitatively assessed by emergy evaluation. Fifth and finally, emergy indices were calculated from emergy data from the previous step, and then indices across cases sharing the same straw reuse-technology were compared. Cases of the various technologies with the best comprehensive benefits were then compared.

2.2. Emergy Indicators

Emergy indicators were used to evaluate the ecological, social, and economic processes of each system (Table 1). EYR is the ratio of the emergy yield from a process to the emergy costs. It is a measure of how much a process contributes to the economy. EYR provides insight into the efficiency of a system by using purchased inputs. ELR is the ratio of non-renewable input emergy used to the renewable emergy used [22]. It is an indicator of the pressure of a transformation process on the environment; thus, it may be considered a measure of the ecosystem stress caused by a production process [23]. ESI is the ratio of the EYR to the ELR. It measures the potential contribution of a resource or process to the economy per unit of environmental load [24].

Table 1. Emergy indicators and calculation formulas.

Indics	Formula	Implications	References
EYR (Emergy yield ration)	(N + R + F)/F	Economic efficiency of straw reuse systems	[22]
ELR (Environmental load ratio)	(F + N)/R	Environmental loading exerted by the straw reuse systems	[23]
ESI (Emergy sustainable index)	EYR/ELR	Sustainability of the straw reuse systems	[24]

2.3. Data Sources

Data for the straw-reuse projects assessed in this paper were collected from the literature and/or estimated from available information and from statistic publications. Tables 2–6 show the basic information available for the cases used in the study. Twenty-five cases were chosen, with five cases for each type of straw-reuse technology (labeled 1–5). The case with best comprehensive benefits was used for comparison among technologies. All cases were from China. The system boundary encompassed renewable energy production only, excluding other processes such as crop plantation, straw transport, and waste disposal.

Table 2. The main characteristics of straw-biogas production cases.

Case No.	Basic information						References
	Tank type	Tank volume	Treatment capacity	Biogas yield	Heating	Straw type	
1	USR	400 m^3	320 tons/year	110,000 m^3/year	biogas & coal	corn straw	[24]
2	USR	720 m^3	500 tons/year	110,000 m^3/year	Biogas	corn straw	[25]
3	CSTR	1000 m^3	548 tons/year	270,000 m^3/year	Coal	corn straw	[26]
4	VPF	500 m^3	460 tons/year	182,500 m^3/year	Biogas	corn straw	[27]
5	CSTR	10 × 50 m^3	480 tons/year	128,000 m^3/year	-	corn straw	[28]

USR: Up-flow solids reactor; VPF: vertical plug flow anaerobic digest process; CSTR: continuous stirred tank reactor. Cases site: #1 Heilongjiang province, Jixi, Mishan; #2 Heilongjiang province, Jiamusi; #3 Heilongjiang province, Qiqihar; #4 Heilongjiang province, Harbin, Bin county; #5 Heilongjiang province, Harin, Tonghe county.

Table 3. The main characteristics of straw-based power generation cases.

Case No.	Basic information					References
	Turboset	Boiler	Time	Generate electricity	Straw type	
1	1 × 25 MW	130 tons/h	6000 h	150,000,000 KWH	corn straw	[29]
2	1 × 30 MW	130 tons/h	7000 h	4,183,000,000 KWH	corn straw	[30]
3	1 × 1500 KW	10 tons/h	5000 h	7,500,000 KWH	corn straw	[31]
4	1 × 30 M	130 tons/h	7000 h	210,000,000 KWH	corn straw	[32]
5	1 × 25 M	2 × 75 tons/h	6000 h	150,000,000 KWH	corn straw	[33]

Cases site: #1 Heilongjiang province, Jiansanjiang farming bureau; #2 Heilongjiang province, Hulin; #3 Heilongjiang province, Bayan county; #4 Heilongjiang province, Hulin farming bureau; #5 Heilongjiang province, Hegang.

Table 4. The main characteristics of straw-briquetting cases.

Case No.	Basic information				References
	Production	Form	Electricity consumption	Straw type	
1	10,000 tons/year	briquetting	60–80 kWh/tons	corn straw	[19]
2	5000 tons/year	pellet	93 kWh/tons	corn straw	[34]
3	5000 tons/year	briquetting	86 kWh/tons	corn straw	[34]
4	20,000 tons/year	briquetting	60–80 kWh/tons	corn straw	[35]
5	81,600 tons/year	briquetting	60–80 kWh/tons	corn straw	[36]

Cases site: #1 Heilongjiang province, Jujin; #2 Heilongjiang province, Zhaodong; #3 Inner Mongolia Autonomous Region, Tongliao; #4 Jilin province, Songyuan; #5 Heilongjiang province, Mishan.

Table 5. The main characteristics of straw-gasification cases.

Case No.	Basic information				References
	Straw gasification furnace	Treatment capacity	Straw gas yield	Straw type	
1	vertical destructive distillation gasifier	183 tons/year	365,000 m^3/year	corn straw	[37]
2	JRQ wet biomass fixed bed gasifier	150 tons/year	300,000 m^3/year	corn straw	[38]
3	JQ wet straw gasifier	280 tons/year	400,000 m^3/year	corn straw	[39]
4	dry distillation-Pyrolysis gasifier	100 tons/year	210,000 m^3/year	corn straw	[39]
5	fuidized-bed gasifier	91 tons/year	365,000 m^3/year	corn straw	[40]

Cases site: #1 Heilongjiang province, Lanxi county; #2 Heilongjiang province, Yanshou county; #3 Heilongjiang province, Daqing; #4 Heilongjiang province, Hulan county; #5 Heilongjiang province, Mudanjiang.

Table 6. The main characteristics of straw-bioethanol cases.

Case No.	basic informations			Pretreatment method	Straw type	References
	Straw input tons/year	Ethonal yield tons/year	Concentration g/L			
1	300,000	50,000	22.0	concentrated sulfuric acid	corn straw	[41]
2	200,000	30,000	20.0	concentrated sulfuric acid	corn straw	[42]
3	2,700	300	24.8	steam-explosion	corn straw	[43]
4	365,000	50,000	24.8	dilute sulfuric acid	corn straw	[41]
5	3,000	300	23.0	dilute alkali acid	corn straw	[44]

Cases site: #1 Heilongjiang province, Shuangcheng; #2 Heilongjiang province, Binxian county; #3 Heilongjiang province, Zhaoyuan county; #4 Heilongjiang province, Qiqihar; #5 Heilongjiang province, Longjiang county.

2.4. Emergy Flow Diagrams

The analyzed processes focused on industrial processing and excluded crop production, harvesting, and transport to the plant. There is no significant difference in agriculture methods and technology among vast cold areas in Northeast China. Except a few state-owned enterprises employing mechanized farming, the main agricultural method is based on family and collective collaboration scales. Since biomass collection and tansportation have been thoroughly anaylzed by many researchers [45,46]. In this study, we focus on the overall benefits of different kinds of straw reuse technology in classic agricultural production in Northeast China. The cases chosen in this paper are shown in Figure 1. Emergy flow diagrams for biogas production, power generation, briquette production, gasification, and ethanol production systems are shown in Figure 2. Each diagram sums the main contributions of inputs and outputs from each technology. Inputs from R consist of straw, water, and renewable energy from the projects. F consists of human labor, maintenance, government subsidies, fossil energy, infrastructure, equipment, and chemical reagents. Y of the systems for biogas production, straw-based power generation, straw briquette production, gasification, and ethanol production are the respective products biogas, electricity, straw briquettes, straw gas, and ethanol. Byproducts of reuse systems include fertilizer (biogas slurry and biogas residue), reductions in greenhouse gas (GHG) emissions, wood tar, and straw carbon. N consists mainly of losses from soil erosion which was negligibled when compared to R. Wood tar is a black mixture of hydrocarbons and free carbon [47].

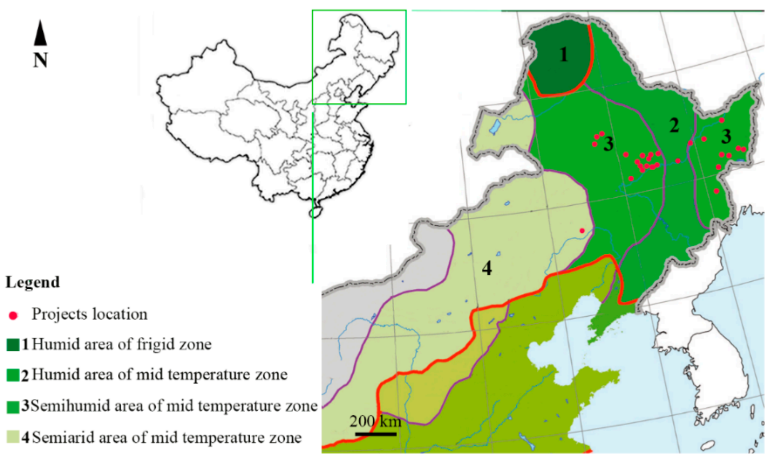

Figure 1. Study sites of the straw reuse technology cases.

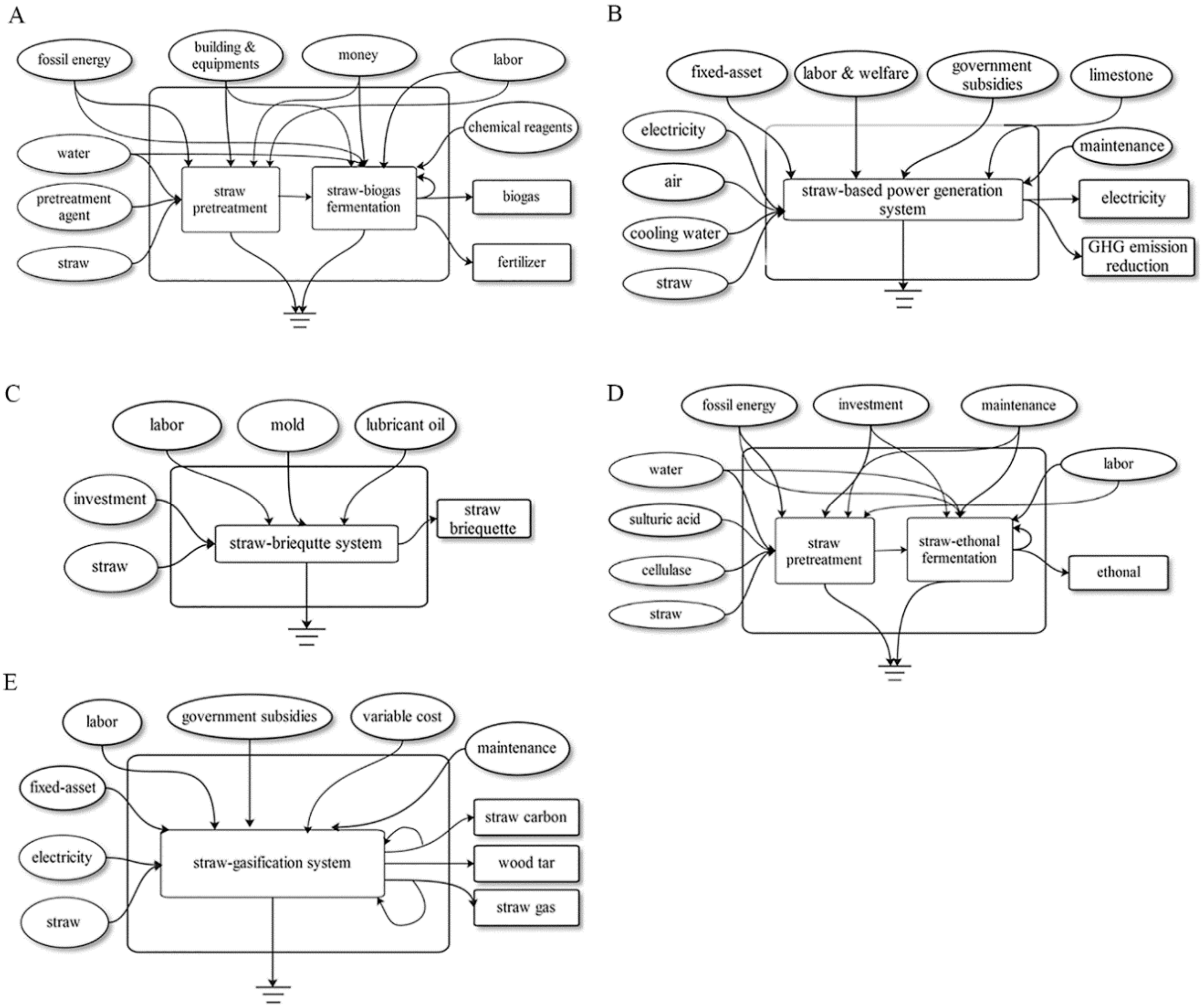

Figure 2. (**A**) Emergy flow of straw-biogas system; (**B**) Emergy flow of straw-based power generation system; (**C**) Emergy flow of straw-briquetting system; (**D**) Emergy flow of straw-ethanol system; (**E**) Emergy flow of straw-gasification system.

3. Emergy Evaluation of the Straw-Reuse Technologies

Respective emergy values for biogas production, power generation, briquetting, gasification, and ethanol production cases are shown in Tables 7–11. Comparative analysis of emergy yield (Y) among straw-biogas, -based power generation, -briquetting, -ethonal and -gasification technology cases (Figure 3). Y is the total emergy output of the system. Y value reflects solar emergy enriched in the system. Emergy yield of five kinds of straw reuse technologies are all above 10^{15} sej/year, and the maximal value is 10^{22} sej/year from straw-based power generation and –ethanol technology cases (Figure 3).

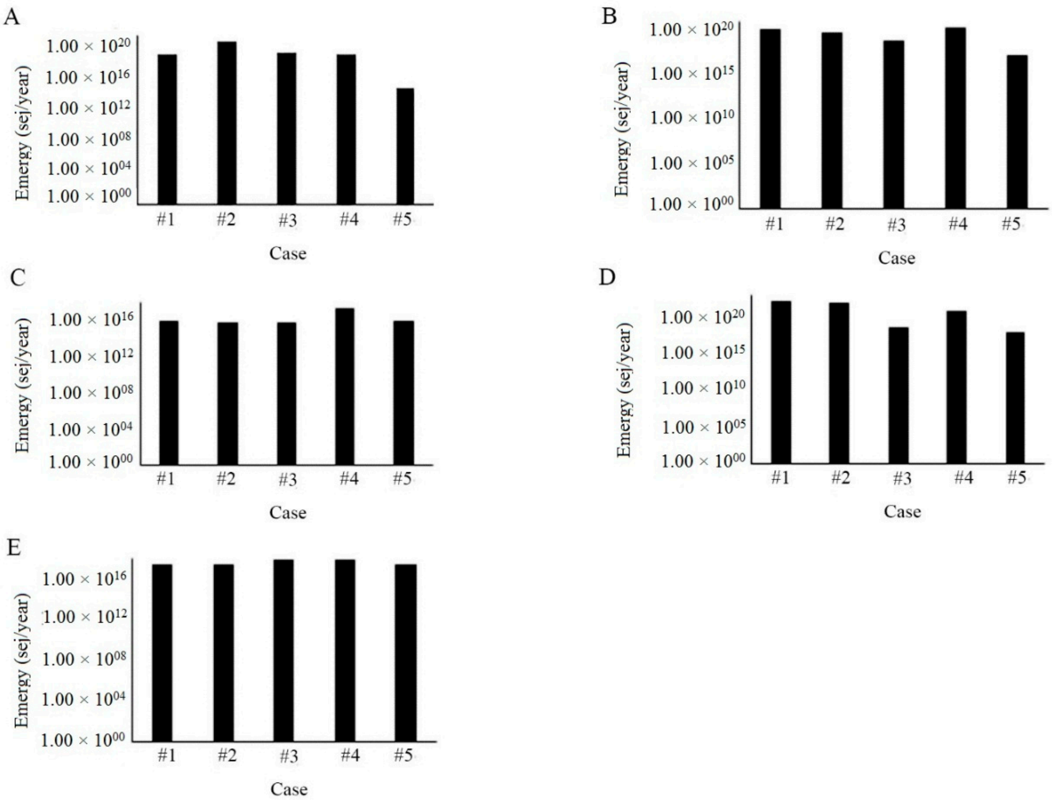

Figure 3. Total emergy of selected cases (**A**) straw-biogas technology, (**B**) straw-based power generation technology, (**C**) straw-briquetting technology, (**D**) straw-ethanol technology and (**E**) straw-gasification technology.

3.1. Cases of Straw-Biogas Production

The total emergy inputs of the five biogas production projects were 7.02×10^{17}, 2.17×10^{19}, 1.32×10^{18}, 7.16×10^{17}, and 7.04×10^{13} sej/year, to which the renewable emergy of the natural ecosystem (R) contributed 40.78%, 20.54%, 40.85%, 20.40%, and 43.49%, respectively (Table 7). The contribution of R was lower than that of nonrenewable emergy from the socioeconomic system (F). Biogas made up 96% of the total emergy yield, with the remainder consisting of biogas residues.

Table 7. Emergy accounting of straw-biogas production technology.

No.	Item	Solar emergy (sej/year)				
		Case No. 1	**Case No. 2**	**Case No. 3**	**Case No. 4**	**Case No. 5**
1	Straw	1.27×10^{17}	1.86×10^{17}	1.92×10^{17}	1.12×10^{17}	2.47×10^{16}
2	Water	1.50×10^{14}	2.61×10^{15}	7.67×10^{13}	5.25×10^{14}	-
3	Biogas(heated)	2.05×10^{17}	-	-	5.46×10^{12}	-
Total natural ecosystem renewable resources (R)		3.32×10^{17}	1.89×10^{17}	1.92×10^{17}	1.13×10^{17}	2.47×10^{16}
4	Investment	-	1.49×10^{17}	2.46×10^{17}	1.19×10^{17}	4.59×10^{14}
5	Building & equipment	3.01×10^{16}	-	-	-	1.53×10^{15}
6	Steel plate	2.45×10^{15}	-	-	-	-
7	Pretreatment agent	-	5.93×10^{12}	-	-	-
8	Nutrient	4.58×10^{13}	5.39×10^{17}	-	-	-
9	Composite microbial agents	-	-	-	-	3.25×10^{15}

Table 7. *Cont.*

No.	Item	Solar emergy (sej/year)				
		Case No. 1	Case No. 2	Case No. 3	Case No. 4	Case No. 5
10	Urea	-	-	-	-	1.66×10^{15}
11	Electricity	1.72×10^{16}	9.19×10^{15}	1.26×10^{16}	1.14×10^{16}	6.76×10^{13}
12	Human labor	6.99×10^{15}	2.29×10^{16}	-	2.87×10^{17}	-
13	Coal	1.93×10^{16}	2.54×10^{17}	1.18×10^{16}	1.93×10^{16}	3.57×10^{15}
14	Maintenance cost	2.99×10^{15}	7.97×10^{15}	7.21×10^{15}	2.39×10^{16}	5.02×10^{14}
15	Desulfurizer	-	3.08×10^{15}	-	-	-
16	Government grants	-	-	-	-	7.97×10^{14}
17	Straw crushing fuel	-	-	-	-	7.15×10^{14}
Total social economic system purchased inputs (F)		7.90×10^{16}	7.31×10^{17}	2.78×10^{17}	4.41×10^{17}	8.91×10^{15}
18	Biogas	6.92×10^{17}	2.11×10^{19}	1.28×10^{18}	7.16×10^{17}	7.04×10^{13}
19	Fertilizer	1.04×10^{16}	6.25×10^{17}	3.63×10^{16}	2.75×10^{14}	-
Total system yield (Y)		7.02×10^{17}	2.17×10^{19}	1.32×10^{18}	7.16×10^{17}	7.04×10^{13}

3.2. Cases of Straw-Based Power Generation

The total emergy inputs of the five straw-based power generation projects were 7.17×10^{20}, 1.17×10^{21}, 9.28×10^{18}, 2.40×10^{20}, and 4.90×10^{20} sej/year, to which R contributed 10%–41%, again lower than the contribution of F (Table 8). Electricity made up more than 50% of the total emergy yield, with the remainder consisting of reductions in GHG emission from the systems.

Table 8. Emergy accounting of straw-based power generation technology.

No.	Item	Solar emergy (sej/year)				
		Case No. 1	Case No. 2	Case No. 3	Case No. 4	Case No. 5
1	Straw	4.02×10^{19}	4.86×10^{19}	3.00×10^{16}	5.51×10^{17}	5.02×10^{19}
2	Cooling water	6.35×10^{18}	1.03×10^{20}	1.51×10^{18}	5.24×10^{19}	5.91×10^{14}
3	Air	3.54×10^{19}	2.96×10^{19}	1.06×10^{16}	2.38×10^{19}	4.03×10^{14}
4	Electricity	4.01×10^{19}	4.46×10^{18}	6.73×10^{17}	2.10×10^{19}	1.44×10^{16}
Total natural ecosystem renewable resources (R)		1.21×10^{20}	1.86×10^{20}	2.22×10^{18}	9.77×10^{19}	5.02×10^{19}
5	Depreciation on fixed-asset	5.14×10^{20}	8.97×10^{20}	1.49×10^{18}	6.78×10^{19}	4.33×10^{20}
6	Labor & welfare	-	4.10×10^{19}	1.25×10^{18}	5.26×10^{18}	5.19×10^{18}
7	Electricity price subsidies	1.71×10^{19}	6.80×10^{18}	-	-	-
8	Investment, operation & maintenance	6.50×10^{19}	4.16×10^{19}	1.73×10^{18}	6.94×10^{19}	1.04×10^{17}
9	Energy	-	-	2.60×10^{18}	-	2.25×10^{18}
10	Limestone	6.64×10^{17}	3.20×10^{18}	2.28×10^{17}	3.20×10^{18}	6.64×10^{17}
Total social economic system purchased inputs (F)		5.96×10^{20}	9.86×10^{20}	7.06×10^{18}	1.42×10^{20}	4.4×10^{20}
11	Electricity	1.29×10^{20}	3.58×10^{19}	6.54×10^{18}	1.56×10^{20}	1.30×10^{17}
12	GHG emission reduction	8.68×10^{18}	2.91×10^{19}	-	7.61×10^{19}	-
Total system yield (Y)		1.38×10^{20}	6.48×10^{19}	6.54×10^{18}	2.31×10^{20}	1.3×10^{17}

3.3. Cases of Straw-Briquetting

The total emergy inputs of the five straw briquetting projects were 9.38 × 10^{18}, 5.81 × 10^{17}, 6.60 × 10^{17}, 1.86 × 10^{19}, and 7.54 × 10^{18} sej/year, to which R contributed 84.43%, 75.73%, 80.00%, 74.11%, and 80.51%, respectively (Table 9). For this technology, R provided a larger contribution than did F. Briquettes were the only product of these projects, with respective yields of 1.08 × 10^{16}, 5.87 × 10^{15}, 5.97 × 10^{15}, 2.64 × 10^{17}, and 1.06 × 10^{16} sej/year.

Table 9. Emergy accounting of straw-briquetting technology.

No.	Item	Solar emergy (sej/year)				
		Case No. 1	Case No. 2	Case No. 3	Case No. 4	Case No. 5
1	Straw	7.92 × 10^{18}	4.40 × 10^{17}	5.28 × 10^{17}	1.38 × 10^{19}	6.07 × 10^{18}
Total natural ecosystem renewable resources (R)		7.92 × 10^{18}	4.40 × 10^{17}	5.28 × 10^{17}	1.38 × 10^{19}	6.07 × 10^{18}
2	Investment	1.98 × 10^{17}	1.17 × 10^{17}	1.06 × 10^{17}	3.82 × 10^{17}	2.05 × 10^{17}
3	Electricity	9.00 × 10^{17}	3.34 × 10^{17}	3.10 × 10^{17}	3.80 × 10^{18}	9.00 × 10^{17}
4	Labor	3.32 × 10^{17}	1.41 × 10^{16}	1.79 × 10^{16}	5.93 × 10^{17}	3.36 × 10^{17}
5	Mold	1.73 × 10^{16}	9.16 × 10^{15}	8.69 × 10^{15}	2.50 × 10^{16}	1.67 × 10^{16}
6	Lubricant oil	9.64 × 10^{15}	4.98 × 10^{13}	4.65 × 10^{13}	2.02 × 10^{16}	1.00 × 10^{16}
Total social economic system purchased inputs (F)		1.46 × 10^{18}	1.41 × 10^{17}	1.32 × 10^{17}	4.82 × 10^{18}	1.47 × 10^{18}
7	Straw briquette	1.08 × 10^{16}	5.87 × 10^{15}	5.97 × 10^{15}	2.64 × 10^{17}	1.06 × 10^{16}
Total system yield (Y)		1.08 × 10^{16}	5.87 × 10^{15}	5.97 × 10^{15}	2.64 × 10^{17}	1.06 × 10^{16}

3.4. Cases of Straw-Ethanol Production

The total emergy inputs of the five production projects for straw ethanol were 4.60 × 10^{22}, 1.41 × 10^{22}, 1.36 × 10^{19}, 2.01 × 10^{21}, and 1.20 × 10^{19} sej/year, to which R contributed 53.48%, 65.79%, 69.85%, 65.17%, and 60.52%, respectively (Table 10). As in the case of briquettes, R had a larger contribution than that of F. Ethanol was the only product of these projects, with respective yields of 1.40 × 10^{22}, 7.77 × 10^{21}, 4.07 × 10^{18}, 6.76 × 10^{20}, and 7.59 × 10^{17} sej/year.

Table 10. Emergy accounting of straw-ethanol production technology.

No.	Item	Solar emergy (sej/year)				
		Case No. 1	Case No. 2	Case No. 3	Case No. 4	Case No. 5
1	Straw	2.46 × 10^{22}	9.26 × 10^{21}	7.25 × 10^{18}	1.31 × 10^{21}	7.25 × 10^{18}
2	Water	7.00 × 10^{19}	2.79 × 10^{19}	2.27 × 10^{18}	5.82 × 10^{17}	2.54 × 10^{15}
Total natural ecosystem renewable resources (R)		2.46 × 10^{22}	9.29 × 10^{21}	9.52 × 10^{18}	1.31 × 10^{21}	7.25 × 10^{18}
3	Investment	1.17 × 10^{17}	1.42 × 10^{17}	6.02 × 10^{17}	3.16 × 10^{20}	6.47 × 10^{17}
4	Energy	7.00 × 10^{20}	6.54 × 10^{20}	3.16 × 10^{17}	2.88 × 10^{16}	4.84 × 10^{17}
5	Labor & maintenance	3.81 × 10^{19}	1.70 × 10^{19}	7.13 × 10^{17}	6.19 × 10^{19}	7.13 × 10^{17}
6	Cellulase	6.16 × 10^{22}	3.27 × 10^{21}	2.16 × 10^{18}	1.73 × 10^{20}	2.21 × 10^{18}
7	Chemical reagents	2.00 × 10^{20}	8.93 × 10^{20}	3.25 × 10^{17}	1.49 × 10^{20}	6.75 × 10^{17}
8	Sulfuric acid	5.67 × 10^{20}	6.45 × 10^{19}	0.00 × 10^{0}	5.30 × 10^{19}	4.18 × 10^{17}

Table 10. *Cont.*

No. Item	Solar emergy (sej/year)				
	Case No. 1	Case No. 2	Case No. 3	Case No. 4	Case No. 5
Total social economic system purchased inputs (F)	2.14×10^{22}	4.83×10^{21}	4.11×10^{18}	7.00×10^{20}	4.73×10^{18}
9 Ethanol	1.40×10^{22}	7.77×10^{21}	4.07×10^{18}	6.76×10^{20}	7.59×10^{17}
Total system yield (Y)	1.40×10^{22}	7.77×10^{21}	4.07×10^{18}	6.76×10^{20}	7.59×10^{17}

3.5. Cases of Straw-Gasification

The total emergy inputs of the five straw gasification projects were 1.45×10^{18}, 9.15×10^{17}, 8.77×10^{17}, 1.65×10^{18}, and 5.93×10^{17} sej/year, to which R contributed 12.47%, 16.28%, 22.69%, 23.54%, and 21.75%, respectively (Table 11), a contribution lower than that of F. Straw gas made up more than 50% of the total emergy yield. Cases 3 and 4 also engaged in byproduct recovery yielding straw carbon and wood tar. Wood tar can be used to preserve timber, rope, *etc.* [47].

Table 11. Emergy accounting of straw-gasification technology.

No.	Item	Solar emergy (sej/year)				
		Case No. 1	Case No. 2	Case No. 3	Case No. 4	Case No. 5
1	Straw	1.81×10^{17}	1.49×10^{17}	1.99×10^{17}	1.20×10^{17}	1.29×10^{17}
2	Straw gas	-	-	-	3.61×10^{16}	-
3	Straw carbon	-	-	-	5.62×10^{17}	-
Total natural ecosystem renewable resources (R)		1.81×10^{17}	1.49×10^{17}	1.99×10^{17}	7.18×10^{17}	1.29×10^{17}
4	Depreciation on fixed-asset	1.12×10^{18}	5.29×10^{17}	4.67×10^{17}	2.03×10^{17}	1.04×10^{17}
5	Electricity	4.29×10^{15}	4.41×10^{15}	1.47×10^{16}	-	2.15×10^{15}
6	Labor	8.46×10^{16}	4.84×10^{16}	1.84×10^{17}	-	6.23×10^{16}
7	Maintenance	6.92×10^{16}	4.15×10^{16}	1.21×10^{16}	-	1.94×10^{16}
8	Subsidies	-	1.42×10^{17}	-	-	2.77×10^{17}
9	Variable cost	-	-	-	7.28×10^{17}	-
Total social economic system purchased inputs (F)		1.27×10^{18}	7.66×10^{17}	6.78×10^{17}	9.31×10^{17}	4.64×10^{17}
10	Straw gas	2.19×10^{17}	1.81×10^{17}	3.22×10^{17}	4.50×10^{17}	1.93×10^{17}
11	Straw carbon	-	-	2.41×10^{17}	1.84×10^{17}	-
12	Wood tar	-	-	-	9.01×10^{16}	-
Total system yield (Y)		2.19×10^{17}	1.81×10^{17}	5.63×10^{17}	7.24×10^{17}	1.93×10^{17}

4. Results and Discussions

The arable land area of northeast China is about 2.61×10^{6} km^2 which is equal to the total land area of New Zealand. Most of the region belongs to continental temperate climate zone, which has extreme seasonal contrasts and enough monsoon rainfall. The number of days, which mean daily temperature over 10 °C, is 100–170 in this area. In addition, the mean temperature in January of this land is between −10 °C to −30 °C. Crop straw production is more seasonal in cold than in warm regions of China, and straw reuse plants would consume more energy in cold environments, which is prohibitive for the development of large-scale straw reuse. To help improve the efficiency of straw reuse under such circumstances, most data used in our study were collected from cold regions of China. As these produce nearly 40% of the country's crop output, this focus was deemed sensible to aid in saving energy and reducing pollution from straw reusing.

4.1. Emergy Analysis of Straw Reuse Systems

In this study, we performed an emergy analysis of five different straw-reuse technologies employed in China and assessed their relative economic and environmental benefits and sustainability. Emergy indices of the investigated straw-reuse cases are listed in Table 12. The emergy indicators ELR, EYR, and ESI were used to compare the various straw-reuse systems that generate different types of products to select the best system. The application of energy evaluation methods in the comparison of different straw reuse technologies improves comparability, objectivity, and accuracy by combining the investigation of energy, money, and material flows.

Table 12. Emergy indices of straw-reuse systems.

Straw reuse technology	Case No.	EYR	ELR	ESI
straw-biogas fermentation	1	5.21	0.24	21.90
	2	1.26	3.87	0.33
	3	1.69	1.45	1.17
	4	1.26	3.91	0.32
	5	3.77	0.36	10.00
straw-based power generation	1	2.00	1.00	2.00
	2	1.10	5.30	0.22
	3	1.31	3.18	0.41
	4	1.69	1.46	1.16
	5	1.11	8.77	0.13
straw-briquetting	1	6.42	0.18	34.85
	2	4.12	0.32	12.86
	3	5.00	0.25	20.00
	4	3.86	0.35	11.06
	5	5.13	0.24	21.18
straw-ethanol fermentation	1	2.15	1.87	1.15
	2	2.92	1.52	1.92
	3	3.31	1.43	2.31
	4	2.87	1.53	1.87
	5	2.53	1.65	1.53
straw-gasification	1	1.14	7.04	0.16
	2	1.20	5.12	0.23
	3	1.29	3.40	0.38
	4	1.99	1.01	1.96
	5	1.28	3.59	0.36

4.1.1. Straw-Biogas Production Technology

Among the fermentation systems for straw biogas production, case 1 had the optimal indices (EYR, ELR, and ESI values of 5.21, 0.24, and 21.90, respectively). This project used biogas and coal to heat a concrete fermentation tank, which had a thermal conductivity lower than that of a stainless-steel tank. Case 5, which used an underground fermentation tank, produced above-average comprehensive benefits as well. This result indicates that heat preservation is a key factor for the straw biogas system.

4.1.2. Straw-Based Power Generation Technology

Projects 1 and 4 had the optimal EYR (2.00 and 1.69), ELR (1.00 and 1.46), and ESI values (2.00 and 1.16) among the straw-based power generation projects. Both projects featured an extraction-condensing steam turbine, while cases 2 and 3 used gas-turbine generators. As case 5 employed advanced equipment and technology from Denmark, its F input was slightly greater. It thus appears that extraction-condensing steam turbines perform well in straw-based power generation systems and that increased investment reduces the comprehensive benefit of the system.

4.1.3. Straw-Briquetting Technology

In the straw-briquetting category, cases 1, 3, and 5 outperformed the other two cases. Whereas the former projects used a briquetting process in production, the latter used granulating processes. Because straw granulation includes a crushing step, the process consumes more energy than does briquetting. This suggests that briquetting is preferable because of the energy savings it enables.

4.1.4. Straw-Ethanol Production Technology

In straw-ethanol production, case 3 had the optimal indices (EYR, 3.31; ELR, 1.43; ESI, 2.31). The main difference of this project from the other cases was the use of steam explosion for straw pretreatment. The other projects used sulfuric acid pretreatment, which generally has higher water and energy consumption. At the same time, steam explosion pretreatment also showed a slight advantage in ethanol concentration, production rate, and saccharification rate, making it the clear preferred choice in straw ethanol production.

Nowadays, the straw-ethanol pretreatment technology used in large scale is concentrated sulfuric acid and dilute sulfuric acid. Straw-ethanol plants which pretreated by steam-explosion and dilute alkali acid methods are still in small scale and pilot systems. In this study the comprehensive benefits were analyzed with practical situations in North China.

4.1.5. Straw-Gasification Technology

In straw-gasification, case 4 showed the optimal indices (EYR: 1.99, ELR: 1.01, ESI: 1.96). This project used a gasification process invented by the Dalian Municipal Design and Research Institute of Environmental Science and incorporates a method for retort pyrolysis gasification. This method improved the rate of waste recovery and yielded byproducts such as straw carbon and wood tar, increasing its relative environmental benefit. The other projects suffered from high environmental impact due to a lack of waste recovery. Byproduct recovery of the straw gasification system thus seems to be the key to improving the system's comprehensive benefits.

In developed countries, straw gasification technology is superior and in large scale. It should be improved urgently in China. Generally, the straw gasification systems are in small scale with low density materials, low fuel gasification conversion, and low fuel combustion value. The straw gasification systems cited in this study show these characteristics and present the real situation in China. Moreover, the agriculture style in North China is one crop a year, which supplies less biomass material. With these disadvantages, the straw gasification technology still shows higher efficiency in straw reuse.

4.2. Comparison among Straw Reuse Technologies

The optimal-scoring projects in their respective categories were case 1 in biogas production (EYR 5.21, ELR 0.24, ESI 21.90), case 1 in power generation (EYR 2.00, ELR 1.00, ESI 2.00), case 1 in briquetting (EYR 6.42, ELR 0.18, ESI 34.85), case 4 in gasification (EYR 1.99, ELR 1.01, ESI 1.96), and case 3 in ethanol production (EYR 3.31, ELR 1.43, ESI 2.31). These projects were chosen because of their overall benefits compared with those of the other cases of different straw-reuse technologies.

4.2.1. Economic Benefits Analysis of Straw-Reuse Technologies

EYR indices for the various cases were respectively 5.21 (straw-biogas), 2.00 (straw-based power generation), 6.42 (straw-briquetting), 3.31 (straw-ethanol), and 1.99 (straw-gasification), suggesting the following ranking of the aforementioned cases by economic benefit: briquetting > biogas production > ethanol production > power generation > gasification (Table 12).

A cost-benefit analysis found that the optimal economic benefit from a straw-based power generation system with an annual power output of 595MW was USD $75.02/MWh [48]. A straw-briquetting implementation with an annual output of 2×10^4 tons/year can yield a net profit of 1.5 million per year [36]. Cost-benefit analyses have the advantage of being simple, straightforward, and well-tested, but do not consider the inputs from natural systems and the value of ecosystem services.

4.2.2. Environmental Benefits Analysis of Straw-Reuse Technologies

ELR is a measure of ecosystem stress based on the utilization of nonrenewable resources from socioeconomic systems. In general, the ELR values of around 2 or less are indicative of relatively low environmental impacts [49]. In this study the respective ELR values are 0.24 (straw-biogas), 1.00 (straw-based power generation), 0.18 (straw-briquetting), 1.43 (straw-ethanol fermentation), and 1.01 (straw-gasification), suggesting the following ranking of the aforementioned cases by environmental benefit: briquetting > biogas production > power generation > gasification > ethanol production (Table 12), indicating that the five straw-reuse technology had almost no deleterious effects on the environment.

When using straw as fermentation material, biogas technologies have a lower environmental impact than do those using wheat and corn [50]. The main method used to evaluate the environmental benefits of straw reuse technologies is life cycle assessment (LCA); using this metric, straw reuse technologies were also shown to compare favorably to coal and natural gas by contributing to GHG reduction [36,51–53].

Bioethanol production will consume more water and produce more GHG per kg of straw than does electricity production [54]. Compared with fossil fuel use, straw-briquetting significantly reduces GHG emissions [36]. Both LCA and energy evaluation analysis can incorporate the natural system's effects on the research system. LCA needs substantial data which makes it difficult to be widely used in China.

4.2.3. Sustainability Potential Analysis of Straw-Reuse Technologies

The ESI index was used to compare sustainability among technologies. ESI values for straw-briquetting and -biogas production (34.85 and 21.90, respectively) were above those of the other technologies, indicating the relatively high potential of these technologies for providing sustainability (Table 12).

The sustainability of power generation using straw-ethanol, -gasification, and -direct combustion is lower than that of straw-biogas or -briquetting. However, the ESI value is greater than 1, which indicates that these systems have the potential to achieve sustainability. Studies that have used the Land Footprint (LF) method or comprehensive evaluation index system on straw-ethanol and -power generation have indicated potential for sustainable development [55–57]. Current research on the potential of sustainable development for straw-reuse projects use comprehensive evaluation [56], LF [55], and comprehensive analysis on all aspects from a quantitative point of view [36,57,58].The LF method is unable to reflect the stress imposed on natural ecosystems (such as soil erosion, reduction of water resources, CO_2 accumulation, *etc*.) by either human activities, or specifically straw reuse technologies. The normalization process of the comprehensive evaluation index system (SEI) is a subjective judgment process, and therefore has a higher tendency to incorporate subjective assumptions.

In this study, quantitative analysis was performed on the sustainability of main straw-reuse technologies. Comparative analysis was performed on other types of technologies to provide a theoretical basis for selecting the technology type. Energy analysis is considered an effective method for assessing the environmental and economic cost and the sustainability of a system under operation. In a unified energy assessment framework, system operational data can be obtained directly or indirectly through the retrospective process of ecological economy. Energy analysis thus has many advantages, including comprehensiveness, unique scales, and visual and intuitive results. In addition, the approach aids in comparing the development path or strategy of different systems, and has a great advantage in evaluating the ecological and economic benefit of a system.

From the above, straw-biogas and -briquetting technology have best "economic-environmental-sustainability" benefits， it is because the biogas from the project can meet the energy needs of farmers; biogas slurry can be used as organic fertilizer for agricultural production. Therefore, straw-biogas technology can improve the ecological-economy value and sustainability of the agricultural system. Additionally， since straw-briquetting technology was developed in China during the 1980s, more equipment has been developed like screw extruding, piston stamping pressing, and roller compacting, which is the most mature one among straw-reuse technologies [53]. Its rapid development has depended on significant financial support from the Chinese government [53]. At the same time, the efficiency of straw-briquetting technology is not very sensitive to cold climates, making it suitable for the cold climatic regions of China.

5. Conclusions

This study presents a comprehensive emergy analysis of various straw-reuse technologies. Some general conclusions can be drawn from the results. Straw utilization is able to increase economic benefits, simultaneously reducing agricultural waste and solving environmental problems. Economic and ecological benefits are therefore equally important for the development of straw resources and energy engineering.

According to comparison of the most efficient projects within each utilization category, the ranking of the five straw-reuse systems based on economic benefits is straw-briquetting > -biogas fermentation > -ethanol fermentation > -based power generation > -gasification system.

Ranking according to environmental benefits is straw-briquetting > -biogas fermentation > -based power generation > -gasification > -ethanol fermentation.

Ranking by potential for sustainable development is straw-briquetting > -biogas fermentation > -ethanol fermentation > -based power generation > -gasification.

On the basis of the above results, straw-briquetting and straw-biogas production provide the highest comprehensive benefits among the straw-reuse projects. Thus, they may be regarded as the most suitable options for straw reuse in cold areas of China.

Author Contributions

Xiaoxian Zhang designed the study, interpreted the data, wrote the manuscript and revised it until its final version. Fang Ma provided good advice throughout the paper and revised the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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