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ORIGINAL PAPER

Comprehensive sustainability assessment of a biogas-linked agro-ecosystem: a case study in China

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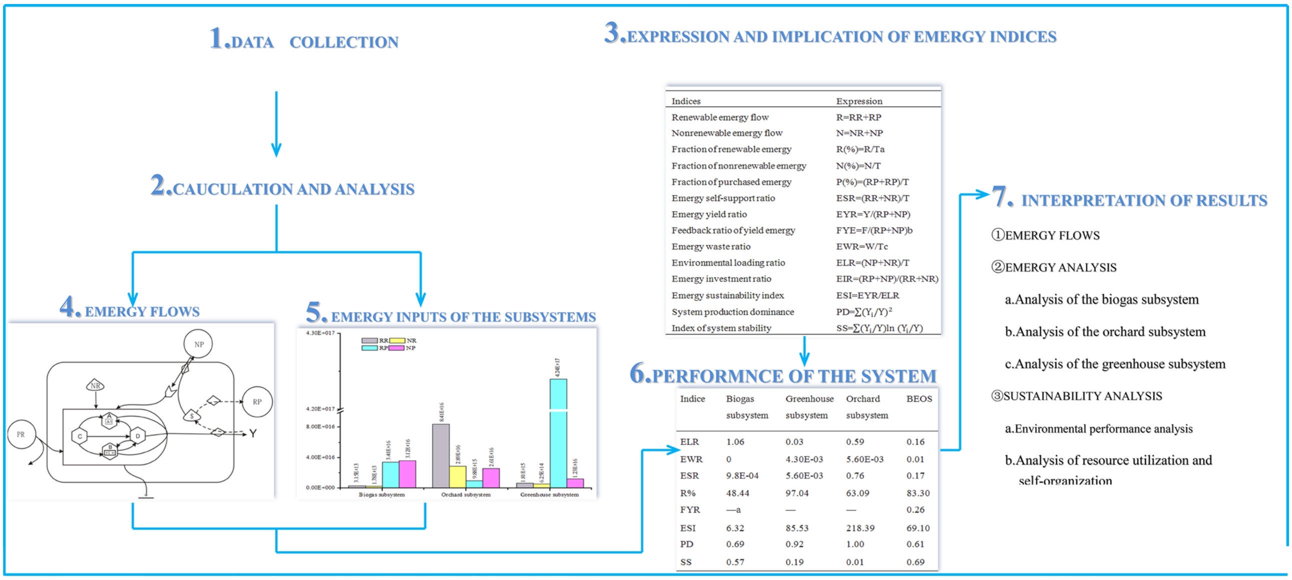
Abstract

The biogas-linked agro-ecosystem plays a critical role in the sustainable development of rural China. In this study, emergy analysis was performed to assess the sustainability of a biogas-linked ecological orchard system in the Loess Plateau area. To analyze the system more comprehensively, the overall orchard system was divided into three subsystems, including the biogas subsystem, the greenhouse subsystem, and the orchard subsystem. Other than the conventional indicators, two novel indicators suitable for orchard ecosystems, the system production dominance and index of system stability, were developed to evaluate the overall performance of the system and subsystems. The results showed significant variations in multiple performances of the subsystems regarding resource utilization, renewability, and production capacity. The circulation of emergy flows among different subsystems revealed a promising renewable capacity and self-organizing ability for the overall system, which further suggests the advantage of this mode in terms of sustainability. As revealed by the emergy indicators, the biogas-linked ecological orchard as an ecological practice is feasible for modern agriculture involving intensive fruit production and breeding, as it can guarantee highly efficient resource recycling and energy conservation without destroying the local environment.

Graphical abstract



Indices	Expression
Renewable emergy flow	R=RR+RP
Nonrenewable emergy flow	N=NR+NP
Fraction of renewable emergy	R(%)=R/Ta
Fraction of nonrenewable emergy	N(%)=N/T
Fraction of purchased emergy	P(%)=(RP+RP)/T
Emergy self-support ratio	ESR=(RR+NR)/T
Emergy yield ratio	EYR=Y/(RP+NP)
Feedback ratio of yield emergy	FYE=F/(RP+NP)b
Emergy waste ratio	EWR=W/Tc
Environmental loading ratio	ELR=(NP+NR)/T
Emergy investment ratio	EIR=(RP+NP)/(RR+NR)
Emergy sustainability index	ESI=EYR/ELR
System production dominance	$PD=\sum(Y_i/Y)^2$
Index of system stability	$SS=\sum(Y_i/Y)\ln(Y_i/Y)$

Indice	Biogas subsystem	Greenhouse subsystem	Orchard subsystem	BEOS
ELR	1.06	0.03	0.59	0.16
EWR	0	4.30E-03	5.60E-03	0.01
ESR	9.8E-04	5.60E-03	0.76	0.17
R%	48.44	97.04	63.09	83.30
FYR	—a	—	—	0.26
ESI	6.32	85.53	218.39	69.10
PD	0.69	0.92	1.00	0.61
SS	0.57	0.19	0.01	0.69

Keywords Sustainability · Emergy · Biogas engineering · Ecological orchard

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Extended author information available on the last page of the article

Introduction

In northwest China, especially in the valley region of Loess Plateau, the apple tree is a dominant specialty crop. According to the yearbook of the National Bureau of Statistics (China Statistical Yearbook 2014), the annual yield of apple in Shaanxi Province reaches more than 10 million tons, which makes Shaanxi the largest apple production province in China (Li et al. 2015). However, the rapid development of the apple industry resulted in many issues including overuse of pesticides and chemical fertilizers (Li et al. 2016). The biogas-linked agricultural production mode is characterized by making a favorable contribution to carbon mitigation and material recycling, especially for the substitution of the chemical fertilizer (Tsukamoto et al. 2012). Hence, the "biogas-linked ecological orchard" system seems to be a good solution to overcome these problems in order to build a better agricultural eco-environment (Wang et al. 2014).

Biogas engineering played a significant role in renewable energy supply (Hijazi et al. 2016), ecological environment conservation (Peter 2010), rural income improvement and the construction of rural civilization (Chasnyk et al. 2015). Since the 1990s, the application of biogas techniques in agriculture has accepted wide attention in China, and a series of biogas-linked agricultural systems have emerged. These systems include the "Four-in-One" peach production system (Wei et al. 2009), the "Cattle–Biogas–Vegetables" system (Zhou et al. 2013), the "Pig–Biogas–Vegetable" system (Qi et al. 2005), the "Pig–Biogas–Rice" system (Liu et al. 2002), the "Pig–Biogas–Fruit (fish)" system (Qi et al. 2012) and the "Biogas-linked Ecological Farm" system (Yang et al. 2011). Almost all such biogas-linked agricultural production modes are closely integrated with their local environments and, therefore, promote local socioeconomic growth to some extent. The development of biogas-linked ecological agriculture in northwest China has many benefits, including improving agricultural production efficiency, protecting the ecological environment, reducing the utilization of chemical fertilizer and pesticides, recycling waste, and creating substantial economic benefits (Liu et al. 2008).

Although various new agricultural patterns have emerged (Han et al. 2013), agriculture is still facing challenges regarding ecology, environment, and energy security (Cavalett et al. 2006). Thus, only by developing sustainable agricultural patterns can we actually solve the fundamental problems.

According to the circular economy theory, the circulating pattern, which was first proposed in China by Gao et al. (2007), has become a universally accepted way for the sustainable development of agriculture (Quezada et al. 2016). Biogas-linked agricultural systems can make full use of various agricultural residues (e.g., livestock and poultry dung) and transform them into cleaner energy, which can mitigate fossil fuel consumption. These systems can eventually form a low-carbon circular economy in rural China (Duan et al. 2011). Currently, there are two main assessment methods for evaluating the agricultural ecosystems, namely macroscale methods (Cabell and Oelofse 2012) and microscale methods (Han et al. 2013). The macroscale methods include the weighting function method, the gray incidence analysis, the fuzzy integrated appraisal, the principal component analysis, the rough set theory analysis, and the data envelopment analysis. The microscale methods focus on life cycle assessment (Chen and Chen 2013), emergy analysis (Cheng et al. 2017), ecological carbon footprint (Hussain et al. 2017), and system dynamics modeling (Webler et al. 2012). Among the above assessment methods, emergy analysis is the only one that can simultaneously show the performance of both the economy and the environment, self-organization and renewability, etc., and has been widely used for assessing the sustainability of circular ecosystems existing at the interface of human and natural systems over the past decade (Wu et al. 2015). To measure and express all kinds of energy in agroecological systems in a more comprehensive manner, the emergy theory and a complete set of emergy concepts were proposed in the 1980s (Odum 1988). Emergy analysis, integrating economic and ecological processes in a common unit, is suitable for evaluating the sustainability of ecological engineering and helps to identify the appropriate agricultural production and consumption mode. During emergy analysis, all types of energies, materials, and monetary flows are converted into a common unit (solar emjoules, sej) through multiplying by the corresponding conversion factors (unit emergy values, UEVs), i.e., transformity (sej/J), specific emergy (sej/g), and the emergy/money ratio (sej/monetary unit) (Lan et al. 2002). The real values of all resources, products, and manpower in a specific ecological system can be calculated using emergy, thus unifying the ecological system with the human socioeconomic system. This approach allows for a comparison among all resources on a fair basis and for discerning the structure and function of complex ecosystems based on different forms of human economic and natural resources (Odum 1996). Thus, emergy analysis can assess various properties, including the profitability, productivity, energy efficiency, and stability of an agricultural system, simultaneously (Ulgiati and Brown 1998).

Recently, research on methods for the evaluation of circular agriculture has become increasingly popular; examples could be found as "Sheep–Crop" (Rodríguez-Ortega et al. 2017), "Pig–Biogas–Vegetable" (Zhang and Chen

2017), "Biowastes-Feedstock" (Saladini et al. 2015), and "Grain–Pig–Fish" (Cavalett et al. 2006). In addition, many new assessment methods were developed in combination with emergy analysis, e.g., emergy–LCA (Liu et al. 2017), emergy–MFA–carbon footprint (Ohnishi et al. 2017), and emergy system dynamics model (Fang et al. 2017). The latest research indicates that the emergy approach is a promising tool for the evaluation of sustainable agriculture systems. However, the application of this method in the evaluation of biogas-linked orchard systems in China has been little investigated (Wu et al. 2015). Moreover, based on the main functions of the system, i.e., planting, breeding, and connection, the biogas-linked ecological orchard system consists of three subsystems. Each subsystem represents a specific agricultural mode, to the best of our knowledge, and few studies have compared the performances of the subsystems to reflect the performance of the integrated system (Yang and Chen 2014). Therefore, it is also valuable to analyze the overall system's sustainability from the subsystem-based perspective. Starting from the structure, function, and operating mechanism of the biogas-linked ecological orchard system (BEOS), this paper investigated a representative biogas-linked ecological orchard system in northwest China.

Above all, the main objectives of this paper are: (1) to understand the sustainability of the overall system and its subsystems via emergy analysis; (2) to evaluate the performances of different subsystems; and (3) to compare the biogas-linked ecological orchard system with other biogas-linked ecosystems and the traditional apple production system.

Additionally, we derived from previous qualitative assessment methods that are suitable for evaluating the production capacities and operation stability of traditional agricultural production ecosystems (Li and Sun 2000) and introduced two new indicators, including system production dominance (PD) and the index of system stability (SS) into the emergy synthesis process in the current study. Using these two indicators in combination helps us to understand the sustainability of the overall system and its subsystems from the perspective of yielding and internal organization.

Materials and methods

Study site

The site selected for this study is located in Chengcheng County of Weinan City (35°15′N, 109°57′E, Shaanxi Province, China). This area is located in the Loess Plateau Gully Region and in a warm temperate zone with semi-humid monsoons. The annual average temperature is 12 °C, with an annual average precipitation of 680 mm. The frost-free period is approximately 204 days, and the average annual solar radiation is 2616 h. In recent years, the cultivation area of the apple tree in Chengcheng was higher than 266.67 km^2 with an annual yield of 40 million tons. This study site has a total of 138 households with more than 600 residents and a total of 0.97 km^2 of arable land, in which the land for the orchard accounts for approximately 0.33 km^2. The leading industries in this area are livestock breeding and fruit production, since the circulating agriculture is highly favored in this area, which owns 123 biogas digesters in total, and over 90% of the households in the study site own a digester (Liu 2013). A survey conducted by Liu et al. (2007) shows that every household in this county owns an apple orchard, with an average area of 3.30×10^{-3} km^2, and raises approximately 11.61 pigs, which helps the farmers gain favorable economic benefits.

Definition of the system

To illustrate the characteristics of the project in Chengcheng, this paper analyzed the structure and function of the BEOS built on farmland. In this system, solar energy was regarded as its energy source and the biogas subsystem was considered as the linkage between crop farming and animal rearing, which together constructed a complex agricultural ecosystem (Liu et al. 2007). The BEOS consisted of five components: the biogas module, the solar heating module, the water storage module, the irrigation module, and the apple planting module. These components included a biogas digester (volume = 8 m^3), a pig house with a solar heating system (area = 12 m^2) surrounded by an apple orchard (area = 3.30×10^{-3} km^2), and a complete drip irrigation system fed by a huge water reservoir, respectively (Fig. 1). Based on the analysis of system functions, the five components were classified into three subsystems, including the biogas subsystem, the greenhouse subsystem, and the orchard subsystem. Among them, the biogas subsystem was a link between breeding and planting and was often built beneath the pig house and a hygienic toilet (Liu et al. 2007). The mixture of manure and flushing water flowed into the biogas digesters through pipelines and can be utilized as a primary feedstock for biogas digestion.

Similar to other biogas-linked ecosystems, the BEOS can produce high-quality fertilizers, such as biogas slurry and residues, which can enhance the growth and fruition of fruit trees (Chen and Chen 2012). Generally, biogas digestate is rich in nitrogen, phosphorus, and potassium, and the apple trees that are receiving digestate will grow stronger with greener leaves. The average commodity rate can reach 85%, and the price is 25% higher than the market average (Liu et al. 2007). Therefore, large-scale implementation of BEOS can generate a wide range of benefits, including stimulating the planting and breeding industries for better development, increasing farmers' income, alleviating the problem of rural

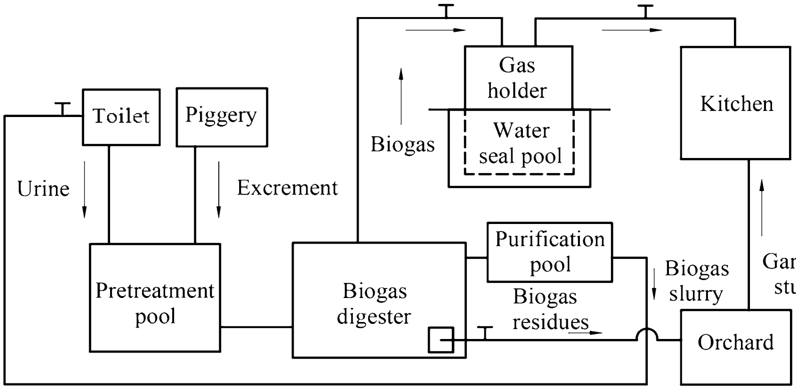

Fig. 1 Structure flowchart of biogas-linked ecological orchard mode

energy shortage, and improving the local ecological environment (Qiu 2001).

Emergy accounting

The BEOS belongs to the category of the agricultural complex ecosystem, so the present emergy analysis followed the general rules and procedures for these ecosystems (Qi et al. 2012). In this study, according to the "emergy system language" proposed by Odum (1996), the emergy analysis of the system was carried out via following steps: (1) draw the emergy flow diagram of the BEOS covering all the environmental resources, purchased renewable and non-renewable resources, system feedback and yield; (2) collect the original data of the overall system and the subsystems, and analyze the characteristics of the emergy flows among the various subsystems; (3) establish an emergy accounting table of the BEOS, which contains the serial number, the original data, solar energy conversion rate or material-energy transformity, emergy units, and the references; and (4) build an evaluation framework that reflects the different

Table 1 Expression and implication of emergy indices

Indices	Expression	Implication
Renewable emergy flow	$R = \mathrm{RR} + \mathrm{RP}$	Total renewable resources from nature, including sunlight, wind, rainfall, human labor, and other purchased renewable resources
Non-renewable emergy flow	$N = \mathrm{NR} + \mathrm{NP}$	Total non-renewable resources from both nature and economy, such as the topsoil loss, ground water, electricity, diesel construction, and maintenance fees
Fraction of renewable emergy	$R(\%) = R/T^{a}$	Ratio of renewable resources to total input
Fraction of non-renewable emergy	$N(\%) = N/T$	Ratio of non-renewable resources to total input
Fraction of purchased emergy	$P(\%) = (\mathrm{RP} + \mathrm{RP})/T$	Fraction of the purchased resources input
Emergy self-support ratio	$\mathrm{ESR} = (\mathrm{RR} + \mathrm{NR})/T$	Ratio of the natural resources invested to the total input
Emergy yield ratio	$\mathrm{EYR} = Y/(\mathrm{RP} + \mathrm{NP})$	Ratio of the output emergy to the purchased emergy. It can evaluates the economic contribution of the output resources to the system
Feedback ratio of yield emergy	$\mathrm{FYE} = F/(\mathrm{RP} + \mathrm{NP})^{b}$	Ratio of the feedback of yield emergy to auxiliary energy, it indicates the system's self-organization ability
Emergy waste ratio	$\mathrm{EWR} = W/T^{c}$	It reflects the environmental pressure generated by the system wastes
Environmental loading ratio	$\mathrm{ELR} = (\mathrm{NP} + \mathrm{NR})/T$	It measures the load on the environment caused by the purchased non-renewable resources
Emergy investment ratio	$\mathrm{EIR} = (\mathrm{RP} + \mathrm{NP})/(\mathrm{RR} + \mathrm{NR})$	It measures the degree of economic development and environmental load
Emergy sustainability index	$\mathrm{ESI} = \mathrm{EYR}/\mathrm{ELR}$	The dependence of a system's output on the environment
System production dominance	$\mathrm{PD} = \sum (Y_i/Y)^2$	It indicates the equilibria between all production units of the system
Index of system stability	$\mathrm{SS} = \sum (Y_i/Y) \ln(Y_i/Y)$	It measures the production stability of the system through checking the system's networks of energy flow and material flow and their feedback

[a] T is the total resources that are input into the system (sej)

[b] F is the feedback resources from the system yield (sej)

[c] W is the wasted resources of the system yield (sej)

performances of the system, explaining and analyzing the various indicators that were carefully selected (Table 1), and establish corresponding strategies or suggestions for optimization and improvement of the BEOS.

Due to the dynamic characteristics of sustainability and the stability of a specific system, the temporal boundary of the complete emergy evaluation studied was limited to the fifteen-year period from 2000 to 2014. This study comprehensively evaluated the environmental and economic inputs to and outputs from the overall system. In this study, PD and SS are developed to evaluate the biogas-linked orchard system's producing efficiency and stability, which are defined as:

$$\mathrm{PD} = \sum (Y_i/Y)^2 \tag{1}$$

$$\mathrm{SS} = \sum (Y_i/Y)\ln(Y_i/Y) \tag{2}$$

where Y_i is the yield emergy of a specific system product and Y is the total emergy yield of the system. Through the calculation of PD, we can determine the quantitative contribution of each production unit of the overall system. SS is designed to show the constancy of system productivity when external interference (e.g., economic, biological, physical and social fluctuations) occurs. The larger the SS, the higher the stability and structural integrity of a system.

Data sources

The original data used for this study were obtained from a field survey (Liu 2013) and the yearbook report (China Statistical Yearbook 2014). To obtain reliable raw data from the field, 120 households were selected at the study site, and all of them were members of the Biogas-linked Ecological Orchard Cooperative in Chengcheng County. In addition to field investigation, the residents as well as the village committee staffs were also invited to fill out the questionnaires about the systems' inputs and outputs. The meteorological data during the service period of the BEOS were obtained through the local weather bureau and the agricultural bureau, and the data were calculated and analyzed mainly by Excel Software (Microsoft Office 2013). The emergy transformity data required for calculation of solar emergy of different system components were obtained from Odum (1996), Wu et al. (2015), Wang et al. (2008), Yang et al. (2010) and Lan et al. (2002), respectively. It is worth mentioning that the emergy transformity of human labor and the conversion from labor force to energy were calculated based on the reports by Wu et al. (2015) and Williamson et al. (2015), respectively.

Results and discussion

Emergy flows in the system

As shown in Fig. 2, the emergy flows of the BEOS included energies and materials derived from natural and purchased resources, and the output emergy flow mainly went into the market and environment. A part of the output emergy was returned to the system for maintaining its operation, and a certain amount of emergy exchange occurred among different subsystems in the BEOS; for example, the total emergy of urine and flushing sewage (4.94×10^{16} sej) produced in the greenhouse subsystem was sent to the biogas subsystem, and all of the biogas slurry and residues (8.70×10^{16} sej) flowed into the orchard subsystem as organic fertilizer. According to previous investigation (Liu 2013) and rigorous calculation of the project in Chengcheng, the fermentation materials produced by the greenhouse subsystem can reach 3040 kg/day. Furthermore, a total of 10,000–15,000 kg manure, which can be converted to a total emergy of 2.36×10^{15} sej/year, flowed into the biogas subsystem every year. The slurry and residues produced by the biogas subsystem provided a nutrient-rich organic fertilizer, which was used to replace a considerable amount of the system's utilization of chemical fertilizers and pesticides. Sometimes, the households substituted all the fertilizers needed in a year by biogas slurry (Wu et al. 2014). The total output emergy of the biogas subsystem was 1.25×10^{16} sej/year, and some of the outputs, like the biogas slurry and residues, flowed back into the orchard subsystem. The biogas accounted for 81.57% of the total output emergy of the biogas subsystem; therefore, it was the most important product of the overall BEOS. It is worth

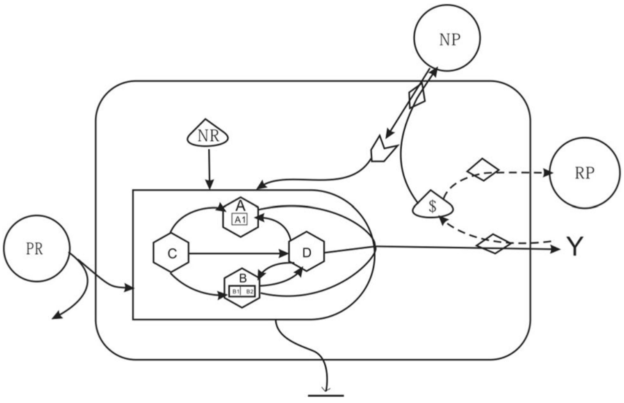

Fig. 2 Emergy flow diagram of the BEOS. A—apple orchard, A1—drip irrigation equipments, B—solar greenhouse, B1—pigsty, B2—household latrine, C—water cellar, D—biogas subsystem, RR—renewable natural resources (sej), NR—non-renewable natural resources (sej), NP—non-renewable purchased resources (sej), RP—renewable purchased resources (sej), Y—yield (sej)

mentioning that the majority of the biogas production flowed into the market, except for a minor proportion that returned to the system for operation.

Emergy analysis of the subsystems

Analysis of the biogas subsystem

The emergy input of the biogas subsystem, orchard subsystem, and greenhouse subsystem is shown in Fig. 3. As the core component of the BEOS, the biogas subsystem plays a significant role in the daily operation of the whole system. The biogas subsystem not only transforms the wasted biomass resources into cleaner energy but also ties the other agricultural sectors together, which makes the BEOS operation more effective and durable. As shown in Table 2, among the purchased emergy inputs, human labor is undoubtedly the dominant item (3.41×10^{16} sej/year). This is mainly due to a series of engineering requirements, such as biogas slurry treatment, material transportation, daily maintenance and construction fees, during the system's life cycle stages. In a short period (e.g., 10 years), the major investments of a biogas project are concentrated in human capital and infrastructure, as a certain amount of human labor is necessary for the lack of advanced mechanical and automated operations. Biogas engineering construction input accounted for 85% of the total non-renewable purchased emergy, which indicated that the project had a large front-end investment and a long payback period (Table 3).

In agricultural ecosystems, clean utilization of biomass is considered "carbon neutral," as the material is regrown in some cases, allowing the carbon emitted during combustion to be reabsorbed. Since biogas is a clean biomass-based energy source, the greenhouse gas emissions generated by biogas combustion can even be neglected when compared with the combustion of coal (Tsukamoto et al. 2012). In this study, biogas accounted for more than 80% of the total output emergy of the biogas subsystem. In addition, the output emergy also included biogas slurry and residues, which were usually utilized as organic fertilizers by the farmers because of the rich nutrient elements and organic matter (Yang et al. 2012). All of the biogas digestion slurry and residues flowed into the orchard subsystem, which is expected to contribute considerably to the goal of "replacing chemical fertilizer with organic fertilizer" in China (Liu et al. 2008).

Analysis of the orchard subsystem

Emergy accounting of the orchard subsystem is shown in Table 4. The natural resources used in the orchard subsystem have a significantly higher complexity than those of the greenhouse subsystem and the biogas subsystem, which lead to stronger dependence on the environment. The emergy input of rainfall (including chemical and potential energy) accounted for 68% of the total renewable environmental resources, indicating that the water resource was the most remarkable factor for apple production. According to the fieldwork of the project, it is clear that the apples produced here have better quality and market value than those produced in the neighboring areas surrounding the study site due to the adequate water supply, large temperature difference between day and night, and the large-scale application of biogas residues as nutrients (Liu et al. 2007).

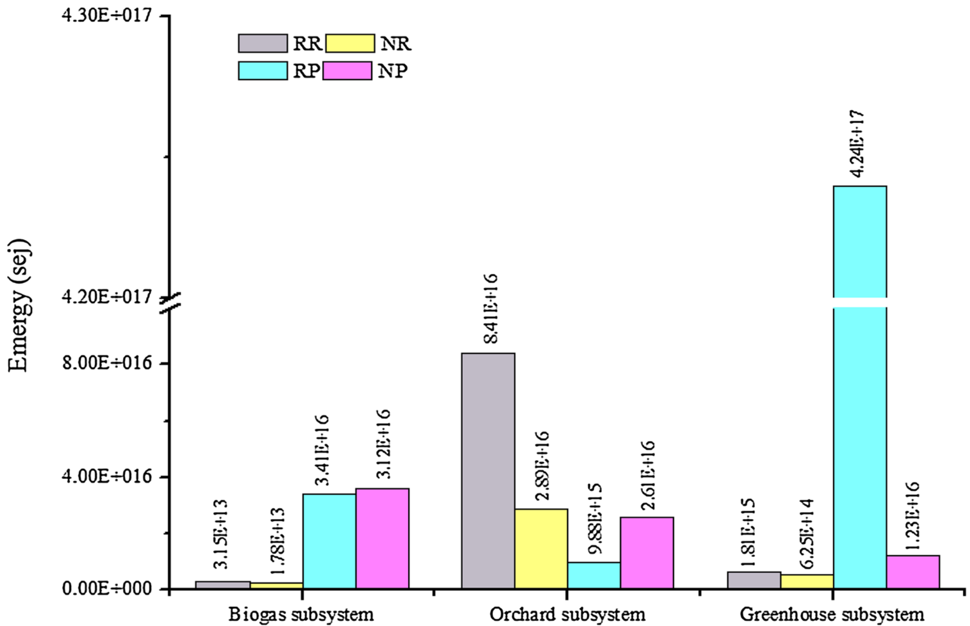

Fig. 3 Emergy inputs of the biogas subsystem, orchard subsystem, and greenhouse subsystem

Table 2 Emergy analysis table of the biogas subsystem

No.	Item	Units	Raw data	Transformity (sej/unit)	References	Solar emergy (sej/year)
Local renewable resources (RR)						
1	Sunlight	J	1.08E+12	1	Odum (1996)	1.08E+12
2	Rain, chemical	J	5.18E+08	18199	Odum (1996)	9.42E+12
3	Wind, kinetic	J	4.22E+09	623	Odum (1996)	2.63E+12
4	Earth cycle	J	4.41E+08	29000	Odum (1996)	1.28E+13
5	Rain, geopotential	J	2.88E+09	8888	Odum (1996)	2.56E+13
Total RR						5.13E+13
Local non-renewable resources (NR)						
	Soil loss	J	2.85E+08	6.25E+04	Odum (1996)	1.78E+13
Total NR						1.78E+13
Renewable purchases from economy (RP)						
	Human labor	J	2.01E+10	1.70E+06	Wu et al. (2015)	3.41E+16
Total RP						3.41E+16
Non-renewable purchases (NP)						
	Biogas Construction	US$	5247	5.87E+12	Yang et al. (2010)	3.08E+16
	Maintenance	US$	637	5.87E+12	Yang et al. (2010)	3.74E+15
	Appurtenant engineering	US$	89.6	5.87E+12	Yang et al. (2010)	5.26E+14
	Diesels	J	1.61E+08	1.11E+05	Yang et al. (2010)	1.79E+13
	Electricity	J	3.39E+09	3.36E+05	Yang et al. (2010)	1.14E+15
Total NP						3.62E+16
Total input						7.04E+16
Yield (*Y*)						
	Biogas	J	1.46E+12	2.64E+05	Wu et al. (2015)	3.85E+17
	Biogas slurry and residue (N)	g	1.17E+07	6.29E+09	Odum (1996)	7.36E+16
	Biogas slurry and residue (P_2O_5)	g	1.42E+06	6.43E+09	Odum (1996)	9.12E+15
	Biogas slurry and residue (K_2O)	g	2.34E+08	1.81E+09	Odum (1996)	4.23E+15
Total yield						4.72E+17

Table 3 Comparison of several chosen emergy indices of different subsystems

Item	Biogas subsystem	Greenhouse subsystem	Orchard subsystem
F%	0.15	0.56	75.84
P%	99.85	99.44	24.16
R%	48.54	97.04	63.09
N%	51.46	2.96	36.91
EIR	1014.43	178.69	0.32
EYR	6.71	2.59	127.78
TR[a]	0.15	0.39	0.03

[a] TR is the solar emergy transformity (Odum 1996)

Among the purchased non-renewable emergy inputs of the orchard subsystem, the use of agricultural machinery and electric power was the primary component, which was mainly attributed to the agricultural operations with high electricity and machinery demands, such as crop planting, fertilization, harvesting, and irrigation. In addition, it is worth mentioning that the organic fertilizer returned to the orchard subsystem replaced approximately 30% of the total investment of pesticides and chemical fertilizers (Liu et al. 2007). The results suggest that the size estimation of the biogas digester, based on the size of orchard, performed at the beginning of the design was accurate.

In terms of the output, the branches and fallen leaves of apple trees had not been effectively utilized, leading to a small amount of waste of the biomass resources. The yield from the apple trees was the dominant benefit in the whole system, with the total output emergy of apples reaching 4.6×10^{18} sej/year and accounting for 74.19% of the total output emergy (6.20×10^{18} sej/year) of the overall BEOS; incidentally, it was reported that the unit price of the sellable apple products was as high as \$0.7/kg (Liu 2013).

Table 4 Emergy analysis table of the orchard subsystem

No.	Item	Units	Raw data	Transformity (sej/unit)	References	Solar emergy (sej/year)
Local renewable resources (RR)						
1	Sunlight	J	1.76E+15	1.00E+00	Odum (1996)	1.76E+15
2	Rain, chemical	J	8.46E+11	18199	Odum (1996)	1.54E+16
3	Wind, kinetic	J	6.89E+12	623	Odum (1996)	4.28E+15
4	Earth cycle	J	7.21E+11	2.90E+04	Odum (1996)	2.09E+16
5	Rain, geopotential	J	4.70E+12	8888	Odum (1996)	4.18E+16
Total RR						8.41E+16
Local non-renewable resources (NR)						
	Soil loss	J	4.62E+11	6.25E+04	Odum (1996)	2.89E+16
Total NR						2.89E+16
Renewable purchases from economy (RP)						
	Human labor	J	5.29E+09	1.70E+06	Wu et al. (2015)	8.99E+15
	Apple seedlings	J	2.55E+10	3.49E+04	Wang et al. (2008)	8.90E+14
Total RP						9.88E+15
Non-renewable purchases (NP)						
	Machinery	US$	1.07E+03	5.87E+12	Yang et al. (2010)	6.30E+15
	Maintenance	US$	5.95E+01	5.87E+12	Yang et al. (2010)	3.49E+14
	Pesticides	g	95.95	1.48E+10	Lan et al. (2002)	1.42E+12
	Fertilizer	g	1.12E+03	2.80E+09	Lan et al. (2002)	3.14E+12
	Diesels	J	1.76E+07	1.11E+05	Odum (1996)	1.95E+12
	Electricity	J	5.80E+10	3.36E+05	Odum (1996)	1.95E+16
Total NP						2.61E+16
Total input						1.49E+17
Yield (*Y*)						
	Apples	J	8.68E+12	5.30E+05	Wang et al. (2008)	4.60E+18
	Branches and leaves	g	2.11E+12	3.49E+04	Wang et al. (2008)	7.36E+16
Total yield						4.60E+18

Analysis of the greenhouse subsystem

Compared to the biogas subsystem, the greenhouse subsystem utilized more renewable energy, probably due to the use of the solar collector and the rearing of livestock, which requires, however, an excessive water supply (Table 5). Renewable purchases from the economy (RP) consisted of human labor, piglets, and fodder, which made emergy contributions of 4.26×10^{15}, 3.63×10^{17}, and 5.68×10^{16} sej/year, respectively, among which the proportion for piglets was the highest (85.61%). Additionally, it can be seen from the emergy accounting that the construction fees, agricultural machinery, and electric power were the main emergy inputs in non-renewable purchases (NP). The output emergy by pigs accounted for 95.58% of the output emergy of the greenhouse subsystem and accounted for 17.79% of the entire system (Fig. 4). The emergy yield of pigs was only lower than apples (75.78%). Thus, the output of pigs was also one of the most important sources of economic benefits in this project.

Comparison of different subsystems

The development of circular agriculture should not destruct the local economy and environment, nor break the biogas-linked ecological orchard system. The comprehensive performance of the BEOS and its subsystems are shown in Tables 3 and 6, respectively. Emergy analysis enabled the economic evaluation of a given system during a certain period of time (Williamson et al. 2015). In this study, the economic comparison between different subsystems was primarily based on the commonly used indicators, e.g., emergy investment ratio (EIR) and emergy yield ratio (EYR). EIR is a ratio of total purchased emergy from the economy to the total emergy of local environmental resources (Williamson et al. 2015), while EYR is widely used for measuring the ability of a process to make local resources available by investing in outside resources (Wang et al. 2015).

Shown in Table 3, the EIR value of the biogas subsystem ranks first, followed by the greenhouse subsystem and the orchard subsystem. As this indicator measures

Table 5 Emergy analysis table of the greenhouse subsystem

No.	Item	Units	Raw data	Transformity (sej/unit)	References	Solar emergy (sej/year)
Local renewable resources (RR)						
1	Sunlight	J	3.80E+13	1.00E+00	Odum (1996)	3.80E+13
2	Rain, chemical	J	1.82E+10	18199	Odum (1996)	3.31E+14
3	Wind, kinetic	J	1.48E+11	623	Odum (1996)	9.24E+13
4	Earth cycle	J	1.56E+10	2.90E+04	Odum (1996)	4.52E+14
5	Rain, geopotential	J	1.01E+11	8888	Odum (1996)	9.01E+14
Total RR						1.81E+15
Local non-renewable resources (NR)						
	Soil loss	J	1.00E+10	6.25E+04	Odum (1996)	6.25E+14
Total NR						6.25E+14
Renewable purchases from economy (RP)						
	Human labor	J	2.51E+09	1.70E+06	Wang et al. (2008)	4.26E+15
	Piglets	J	2.12E+11	1.71E+06	Wang et al. (2008)	3.63E+17
	Fodder	J	8.35E+11	6.80E+04	Wang et al. (2008)	5.68E+16
Total RP						4.24E+17
Non-renewable purchases (NP)						
	Equipment amortization	US$	204.43	5.87E+12	Yang et al. (2010)	1.20E+15
	Maintenance	US$	153	5.87E+12	Yang et al. (2010)	8.96E+14
	Greenhouse construction	US$	1356	5.87E+12	Yang et al. (2010)	7.96E+15
	Appurtenant engineering	US$	38.33	5.87E+12	Yang et al. (2010)	2.25E+14
	Diesels	J	1.10E+08	1.15E+05	Odum (1996)	1.27E+13
	Electricity	J	6.07E+09	3.36E+05	Odum (1996)	2.04E+15
Total NP						1.23E+16
Total input						4.39E+17
Yield (*Y*)						
	Pigs	J	6.32E+11	1.71E+06	Odum (1996)	1.08E+18
	Urine and flushing sewage	J	5.05E+08	3.72E+06	Wu et al. (2015)	1.88E+15
	Pig manure	J	1.79E+12	2.65E+04	Wu et al. (2015)	4.75E+16
Total yield						1.13E+18

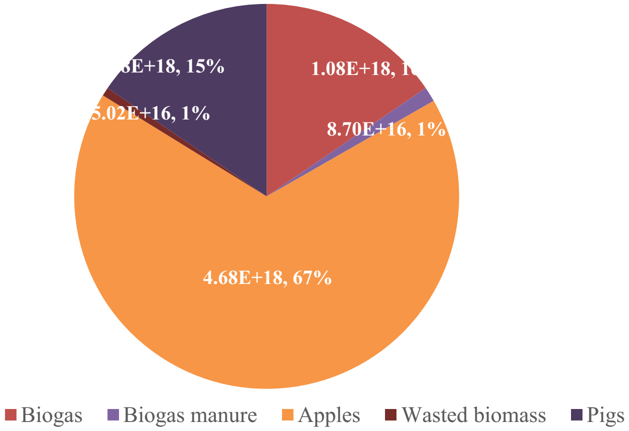

Fig. 4 Emergy outputs of the BEOS

the ratio of emergy invested into the system from outside (that is, from the economy) to locally utilized renewable emergy, the biogas subsystem is therefore less economically efficient than the other subsystems, while the orchard subsystem is the most sustainable in the economy. At the same time, the EYR values from maximum to minimum are the orchard subsystem, the biogas subsystem and the greenhouse subsystem. The relatively low EYR for the first two subsystems indicates that local resources are not being as fully exploited in the greenhouse subsystem and the biogas subsystem, compared with the orchard subsystem. Above all, we found that the orchard subsystem showed the best economic performance and owned the merits of less investment and higher production efficiency, mainly because of the different functions that the subsystems have. In brief, the greenhouse subsystem can produce various feedstock (e.g., livestock feces) for other subsystems, while the orchard subsystem is only capable of producing fruits and vegetables. Moreover, the biogas subsystem

Table 6 Emergy indices of the BEOS and other representative agricultural systems

Indice	Biogas subsystem	Greenhouse subsystem	Orchard subsystem	BEOS	PBGS (Sun et al. 2015)	BEVS (Duan et al. 2015)	SAPS (Wang et al. 2008)	Chinese agricultural system (Jiang et al. 2007)
ELR	1.06	0.03	0.59	0.16	0.17	0.15	2.77	7.83
EWR	0	4.30E−03	5.60E−03	0.01	0	3.94E−03	1.33E−02	–
ESR	9.8E−04	5.60E−03	0.76	0.17	5.00E−03	3.30E−02	0.23	0.39
R%	48.44	97.04	63.09	83.30	86.77	86.77	26.48	25.00
FYE	–	–	–	0.26	0.17	0.43	0	1.02
ESI	6.32	85.53	218.39	69.10	69.93	43.16	0.97	0.13
PD	0.69	0.92	1.00	0.61	0.88	0.57	0.76	0.72
SS	0.57	0.19	0.01	0.69	0.25	0.82	0.48	0.92

– Imponderable data

functioned well as a bridge between planting and breeding (Duan et al. 2015).

As for environmental performance, the system and subsystems can also be interpreted by emergy analysis using different indicators. The environmental loading ratio (ELR) is the ratio of non-renewable over renewable inputs, which is often used to assess the environmental load caused by the system (Baral et al. 2016). In this study, ELR indicates the environmental load and pressure of the biogas-linked ecological orchard on its surroundings. The ELR value of the three subsystems was 1.06 (biogas subsystem), 0.59 (orchard subsystem), and 0.03 (greenhouse subsystem), respectively. Compared with the traditional apple production system (Wang et al. 2008), the ELR of 0.16 for the biogas-linked ecological orchard system is much lower, implying that this system puts less pressure on the environment, owning to a large proportion of renewable resources, especially animal and human excreta. The emergy waste ratio (EWR) value of the overall system was only 1.26%, suggesting that the system has a good internal recycling mechanism and the wastes produced by the system were reused mostly with little adverse impact on the environment. Furthermore, as shown in Table 6, the ESR value [an indicator that indicates the proportion of total emergy input from local natural resources (Odum 1996)] of the BEOS was 0.17, and the *R*% value was 83.30%, which illustrated that the natural resources contributed the most to the system, evidencing that the system has higher resource utilization efficiency. Among all the subsystems, the ESR value of the orchard subsystem was 0.76, which was significantly higher than others, and even higher than the combined system. This indicates that the ordinary operation of the orchard subsystem mainly depended upon renewable resources from the local environment; for example, the growth of the apple tree mainly depended on sunlight, rainfall and soil. In contrast, the biogas subsystem and greenhouse subsystem required more unnatural resources. The reason we included indicators such as EWR and ESR in environmental analysis is because the degree of non-renewable resources utilization could have direct impacts on the local environment.

Sustainability evaluation

The BEOS can be regarded as an energy system in terms of its biogas module, with an overall life cycle of 15 years. According to the study by Campbell and Garmestani (2012), although sustainability is a dynamic character of a specific system, it is related to the emergy flows that maintain the current system state, and thus, a reliable evaluation result can be reached with the selected emergy indicators. In this study, we evaluated the sustainability mainly by determining the fraction of the total renewable emergy used by the system, as well as the ESI results, which naturally combines the economic and environmental factors in a system. In addition, two novel indicators, including PD and SS, were used to evaluate the comprehensive performance of the present system. The *R*% values of the greenhouse subsystem, the orchard subsystem, and the biogas subsystem were 97, 63, and 48%, respectively. The greenhouse subsystem ranked the highest, probably due to the high inputs of animals, feed, and other purchased renewable resources. For the maintenance of the whole system, all of the biogas residues and livestock manure, together with some of the biogas, were returned to the BEOS as feedstock and accounted for approximately 26% of the overall emergy output. The *R*% of the BEOS, the “Pig–Biogas–Grain” system (PBGS), and the biogas-linked eco-village system (BEVS) were significantly higher than both the single apple production system (SAPS) and the Chinese agricultural system as a whole, which showed the advantage of the biogas-linked systems in its self-renewal capacity. It is also worth mentioning that the EWR of the BEOS was higher than those of the PBDS and the BEVS, and the main reason leading to this phenomenon was that the apple branches and leaves were not used effectively. If we make full use of the surplus apple branches and leaves, the sustainability of both the BEOS and each subsystem can be improved dramatically.

The ESI values of the three subsystems showed that the orchard subsystem and the greenhouse subsystem were of higher sustainability. According to the accounting results, the degree of utilization of resources was relatively underdeveloped due to limitations in science and technology application, although the sustainability of the whole system was excellent when we consider the ESI values (Zhang and Chen 2017). In addition, the ESI values of the three biogas-linked ecosystems, i.e., the BEOS, PBGS (Sun et al. 2015) and BEVS (Duan et al. 2015), were not obvious, but they were both significantly higher than that of the conventional apple production system and the Chinese agricultural system. It is thus concluded that the BEOS is on a relatively high level of sustainability compared to other existing orchard systems in China.

PD and SS (Table 1) were two novel indicators that were proposed in the present study for the evaluation of agricultural ecosystems. Specifically, PD was developed to illustrate the equilibria between all production units of the system; thus, a lower PD value indicates higher system stability or better sustainability for production. For SS, as defined by Eq. (2), the higher value normally represents a better system structure and a more efficient flow network of energies and materials. From Table 6, there are no significant differences in PD results between the present system and the four reference systems. However, the PD values of the subsystems from high to low were in the order of the biogas subsystem < the greenhouse subsystem < the orchard subsystem. In contrast, the SS values showed a reverse change trend, i.e., the orchard subsystem < the greenhouse subsystem < the biogas subsystem (Table 6). As shown in Table 6, the PD value of the biogas subsystem ranked the lowest, which indicated that the product value of this subsystem was relatively insignificant, so further exploration and optimization on the system structure are necessary (e.g., methane purification). As shown in Table 6, the biogas subsystem had the highest stability coefficient, followed by the greenhouse subsystem and the orchard subsystem, which was mainly because of the well-developed connection networks for material flows and energy flows within the biogas subsystem and its excellent self-control capacity and recycling function. In terms of the productive practice, which is an important link between the planting and breeding industry, biogas engineering played a vital role in maintaining the sustainability of the whole system.

The previous two indicators for the overall system's sustainability evaluation (i.e., *R*% and ESI) were more likely to lie in between the maximum value of the three subsystems and the minimum. The *R*% value of the overall system (83.30%) was higher than that of the biogas subsystem (48.44%) but lower than that of the greenhouse subsystem (97.04%). Similarly, the ESI value of the overall system was higher than that of the biogas subsystem, while lower than that of the orchard subsystem (Table 6). This could be explained by the fact that the combination of the three subsystems is able to homogenize the resource utilization and promote the exchange between different sectors. However, the results of PD and SS showed the superiority that the BEOS have as a "larger system," which is relative to the basic units of a system, and it is clear that the aggregation of different system functions (e.g., the planting and breeding industry in this study) can effectively improve the network structure of various emergy flows and ultimately strengthen the system stability (Campbell and Garmestani 2012). It is obvious that the coordination of different indicators, including ESI and *R*%, as well as PD and SS, can generate more reliable emergy assessment results; sometimes these indicators can verify each other to support a specific conclusion. Although some of the evaluation results of the overall system are not as well as that of the subsystems, the BEOS as a whole can effectively reduce the most glaring omissions of these subsystems with different functions. The three subsystems are closely correlated and inseparable, constituting the organic whole of the overall system. The investigated system showed every potential in promoting the healthy development of the local economy, ecology and society.

Conclusions

Emergy analysis was used as a useful tool to evaluate the sustainability of complicated agricultural systems. The results showed that the orchard subsystem was more dependent on the renewable resources than other subsystems, while the biogas subsystem was proven to be more dependent on non-renewable resources in terms of construction, maintenance and fuels. In contrast, the greenhouse subsystem ranked the first in terms of renewability, probably due to plentiful inputs of the purchased renewable resources. Through economic comparison between different subsystems, it is clear that the orchard subsystem showed the best economic performance and owned the merit of the least investment with a higher production efficiency. It is worth mentioning that in the long term, the socioeconomic performance of an agricultural system also plays a significant role in sustainability. The ecosystem with a higher EYR and a lower EIR, such as the greenhouse subsystem, will be more likely to succeed in economic competition than those ecosystems that consume a high amount of non-renewable resources, which are limited. The biogas subsystem had a lowest PD value but a highest SS value, mainly due to its complex recirculating networks of energy, matter, information, greater variety of products, and simplicity of the planting sector (i.e., the orchard subsystem). As a result, the orchard subsystem, as a critical component of the overall system, could achieve the most economical profit but with the worst stability throughout its life cycle. In contrast, the biogas subsystem had the best stability and functioned as an ideal bridge between energy utilization and environmental protection for the breeding and planting sectors.

For the evaluation of the overall system's sustainability, this study mainly focused on $R\%$, ESI, and the coordination of PD and SS. The indicators showed that all the biogas-linked ecosystems had better sustainability than the single apple production system and the Chinese agricultural system as a whole in terms of resources utilization. The BEOS had a greater SS but a lesser PD than the single apple planting system; this revealed that a multifunctional system could be stronger (i.e., a better self-organization capability and greater potential for sustainable development) than a single-function system but may not be as productive. The ELR of the BEOS suggested that the amount of renewable resources utilization is greatly higher than the non-renewable resources, which is significantly larger than the ratio for the single apple system and the Chinese agricultural system. All of these results together revealed that the BEOS had better comprehensive performances due to the efficient utilization of the various emergy flows. Therefore, promising environmental benefits in rural areas of China could be obtained by implementing the biogas-linked ecological orchard mode.

In general, although some indicators of the overall system were not as good as its subsystems, the BEOS showed higher sustainability than any individual subsystem. The main reason lies in the internal metabolism of material flows within the system, which reflects the renewability of biogas engineering. With byproducts of biogas production, such as biogas slurry and residues flowing into other subsystems, environmental stress can be alleviated and sustainable breeding and planting subsystems can be gradually achieved. Thus, further efforts should be made to maximize the utilization of the apple tree branches, fallen leaves, biogas slurry, and residues in the orchard and greenhouse subsystems, e.g., by using biogas residues and apple tree branches (in the form of compost) to substitute for chemical fertilizer and using biogas slurry as feed and for soaking seeds. The economic and environmental impacts of a multifunctional agro-ecosystem are also of critical importance; thus, based on the space and time-dependence of the sustainability concept, optimization schemes of such systems should always focus on the comprehensive sustainability indexes according to the local development goals.

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Author contributions CGZ and LQ designed the study together; CGZ provided the figures and tables of the manuscript and wrote the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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