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RESEARCH ARTICLE

Impacts of biogas projects on agro-ecosystem in rural areas — A case study of Gongcheng

Jin YANG[1], Weichao CHEN[2], Bin CHEN (✉)[1]

1 State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China
2 Guangxi Administration Centre of Foreign-Funded Project for Agricultrue, Nanning 530022, China

Abstract The rapid growth of agro-ecosystem has been the focus of "New Rural Construction" in China due to intensive energy consumption and environmental pollution in rural areas. As a kind of renewable energy, biogas is helpful for new energy development and plays an important role in the sustainable development of agro-ecosystem in China. To evaluate the effects of biogas on agro-ecosystem from a systematic angle, we discussed the status quo of household biogas and identified its main factors that may have impacts on agro-ecosystem. An indicator framework covering environmental, social and economic aspects was established to quantify the impacts exerted by biogas project on agro-ecosystem. A case study of Gongcheng was then conducted to evaluate the combined impact of biogas project using the proposed indicator framework. Results showed that there was a notable positive effect brought by the application of biogas, and the integrated benefit has been significantly improved by 60.36%, implying that biogas as a substitute energy source can promote the sustainable level of rural areas.

Keywords biogas, agro-ecosystem, sustainable development, Gongcheng

1 Introduction

Biogas as a linkage of agro-ecosystem is of great importance in propelling the sustainable development of rural areas. As a new kind of energy source, biogas can reduce the traditional domestic consumption of firewood and coal and thereby alleviate the environmental pressure. In addition, as the substitute of chemical fertilizer, biogas slurry and residue could promote the development of cropping by improving soil quality. Meanwhile, social and economic benefits can be obtained through the biogas projects, e.g., improvement of rural sanitation and incomes of farmers.

Many researches have emerged regarding the economic feasibility of biogas projects (Brown et al., 2007; Wang et al., 2007; Yiridoe et al., 2009). Environmental impacts issues have also been investigated, e.g., Zhang et al. (2007) quantified the reduction in CO_2 and SO_2 emissions, which results from the substitution of household biogas in place of traditional biomass energy and coal from 1996 to 2003. Berglund and Börjesson (2006) analyzed the energy balances from a life-cycle perspective for biogas systems based on eight different kinds of raw materials. Particularly, the opportunities and constraints of households biogas use in China were summarized by Chen et al. (2010).

However, the multifaceted impacts of biogas projects in rural areas ought to be quantified by selecting a range of specific indicators. The application of biogas has significant influences on the agro-ecosystem from the aspects of resource, environment, technology, economy and society. Since the biogas project is dedicated to promoting the sustainable development of agro-ecosystem, the indicators evaluating the impact of biogas project on agro-ecosystem should give priority to the trade-offs between its economic, social and ecological objectives that reach acceptable values for the society as a whole (Hediger, 1999; Stoorvogel et al., 2004).

This paper aims to establish an indicator system including environmental, economic and social factors to reflect the influence of biogas on sustainable development through questionnaire investigation and calculation. Using the 5-point grade system, and analytic hierarchy process (AHP) method, we determine the overall score and categorize it into the corresponding grade to quantify the compound effects of biogas projects.

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E-mail: chenb@bnu.edu.cn

2 Methodology

2.1 Study site

Gongcheng is located in the north-east of Guangxi Zhuangzu Autonomous Region, which has a humid subtropical monsoon climate. The annual average temperature is 19.7°C, with the annual precipitation of 1439.7 mm. It covers an area of 2149 km^2, in which the arable land area is 182.1 km^2. There are 9 towns including 117 villages in total, and the population is 0.25 million.

Biogas has been widely used since 1983 to shape a biogas-linked agricultural ecosystem in Gongcheng. The promotion of biogas was further accelerated and intensified from the year of 2009. More than 89% of the households have built their own biogas digesters, and the total number of biogas digester has reached 63600. By the end of 2009, the total agricultural output value had amounted to 1941 $\times$ 10^6 CNY, and the net income per capita reached 4630 CNY, with forest coverage rate roaring to 77.09%.

2.2 Establishment of indicator system

The multiple benefits of biogas project in rural areas include: improving the food supply by producing more and better crops, fruits, and pigs, increasing the efficiency of agricultural production, and reducing the soil erosion. Positive effects for human health result from the elimination of parasites by the biogas fermentation process and the use of biogas for cooking instead of dung or wood. However, the construction of biogas digesters may occupy former arable land and the construction costs are not affordable for some farmers. Based on the potential impacts of biogas exerted on sustainable development, an indicator system is thereby proposed. Major impacts related to social, economic and environmental aspects caused by the application of biogas are identified and classified in Table 1.

2.3 Data sources

A great deal of basic data collection, status investigation and consultation for experienced experts in biogas production are conducted, and then the basic information is obtained. The value of each indicator is thereby determined by virtue of questionnaires and basic calculations. Environmental impacts are represented as a changing rate, which is obtained by comparing the performance under the condition that 90% of the households have turned to use biogas as a major energy source in 2009 with that of non-biogas application period in 1983, as listed in Eqs. (1)–(6), while the values of social and economic indicators are obtained directly from the questionnaires by comparison between biogas households and non-biogas households.

1) The impact on soil quality by the increase in organic fertilizer is depicted as below:

$$a = G_{\text{or}}/F = [N_t \times (g_{\text{residue}} \times a_{\text{residue}} \times \theta_{\text{residue}} + g_{\text{slurry}} \times a_{\text{slurry}} \times \theta_{\text{slurry}} + g_{\text{straw}} \times a_{\text{straw}} \times \theta_{\text{straw}})/S]/F, \tag{1}$$

where a is the proportion of the chemical fertilizer substituted by organic fertilizer; G_{or} is the organic matter increased in the soil; S is the arable land area; F is the background value of soil; N_t represents the number of biogas digesters that are under operation; g_{residue}, g_{slurry}, g_{straw} are the residue, slurry produced and straw saved by biogas production per household, respectively; a_{residue}, a_{slurry}, a_{straw} stand for the proportion of residue, slurry and straw that are put into the farmland to fertilize the soil, respectively; θ_{residue}, θ_{slurry}, θ_{straw} are the organic matter contained in residue, slurry and straw, here we use 33.2%, 1.29% and 12%, respectively.

2) CO_2 emissions caused by biomass burning and coal combustion are demonstrated in Eqs. (2)–(4):

$$C_W = N_t \times W \times 45\% \times 87\% \times 44/12 = 1.436\, N_t \times W, \tag{2}$$

$$C_S = N_t \times S \times 40\% \times 85\% \times 44/12 = 1.247 N_t \times S, \tag{3}$$

$$C_C = N_t \times C \times 0.0209 \times 24.26 \times 80\% \times 44/12 = 1.487\, N_t \times C, \tag{4}$$

where C_W, C_S and C_C are CO_2 emissions caused by the combustion of firewood, straw and coal, respectively; W, S and C represent the firewood, straw and coal saved per household due to the substitution of biogas with the unit of t, respectively; 45%, 40% are the coefficients of carbon contained in firewood and straw, respectively; 87%, 85% and 80% are the carbon oxidized rates of firewood, straw and coal, respectively; 0.0209 is the calorific value and 24.26 is the carbon emission factor of coal with the unit of TJ/t and t/TJ, respectively.

Thus, the proportion of decreased CO_2 emission is calculated as below:

$$c = (C_W + C_S + C_C)/C_0, \tag{5}$$

where C_0 is the CO_2 emission before the application of biogas.

3) The quantity of SO_2 emitted currently is calculated and compared with the non-biogas use period, as Eqs. (6) and (7) shown.

$$S_C = N_t \times C \times 16 \times 84\%/1000 = 0.0134C, \tag{6}$$

$$e = S_C / S_0, \tag{7}$$

where S_C is the reduced SO_2 emission; S_0 is the SO_2 emission during the non-biogas period.

4) The reduction of deforestation rate can be represented as f in Eq. (8).

$$f = W \times N_t / W_0, \tag{8}$$

where f represents the reduction rate of forest deforestation; W_0 stands for the firewood consumed per year before the construction of biogas digester.

5) The proportion of harden land owning to biogas digester construction is calculated using the total construction area of biogas digester divide by the total area of arable land.

6) The proportion of disposed excreta is used to illustrate the impact on hygienic conditions of rural area.

According to the influence level caused by household biogas projects, all these rates calculated are normalized to a five-grade classification, as shown in Table 2. The impacts of biogas on different aspects are summarized into two categories covering both beneficial impacts and passive impacts. A detailed classification is made further to distinguish the different influencing levels. A five-grade classification is finally determined, which includes the grades of severe impact, big impact, moderate impact, slight impact and minor impact.

2.4 AHP

AHP has been one of the most widely used multiple criteria decision-making tools in the hands of decision makers and researchers (Vaidya and Kumar, 2006). We employ it in this paper to evaluate the impacts of biogas on agro-ecosystem. Based on the framework established in Table 1, the important levels of factors that are in the same layer are decided by pairwise comparisons. According to the scale set made by Satty (1992), we get the weight of each element by comparing these pairs. Finally, the weight of each indicator to the destination layer is obtained layer by layer. To evaluate the impacts of biogas on sustainable development objectively, we dispatch the comparison tables to the local decision makers and researchers dedicated to this field.

3 Results and discussion

We collected the questionnaires, identified the weight of each indicator, and finally confirmed the weight by consistency check. With the weight determined, the results of comprehensive evaluation are obtained, as shown in Table 3.

As can be seen, the complex influence is 5.44, which is approximate to moderate beneficial impact according to Table 2, implying that biogas as a substitute energy source is helpful to promote the sustainable development of agro-ecosystem. Although some passive impacts have been brought about by the construction of biogas digesters, they can be ignored, e.g., the cost of biogas digester construction is −1.7, which is between minor and slight adverse impact. Therefore, the future development of biogas should be attached great importance in order to increase the current moderate beneficial impact on agro-ecosystem to large and significant beneficial impact. This result provides decision makers with convincing evidence in generalizing the biogas linked-ecological agriculture mode of Gongcheng to the whole Guangxi Zhuangzu Autonomous Region.

The impacts of the biogas project on environmental, social and economic subsystems are demonstrated in Table 4. it can be found that the value of environmental impact brought by biogas is 5.86, which contributes most to the total benefit in Gongcheng. i.e., the application of biogas has produced large environmental and ecological benefits, especially its significant role in decreasing the deforestation area, increasing animal excreta disposal rate and reducing CO_2 emission, as shown in Table 3. The value of impacts on decreasing the deforestation area, increasing animal excreta disposal rate and reducing CO_2 emission are 8.55, 7.8 and 5.12 respectively. Thus, the spread of biogas project is of great importance for sustainable development of agro-ecosystem, especially for the protection of forests and construction of "low-carbon village."

As biogas could be used in many ways to increase the agricultural output, there is a promotion in economic benefit in Gongcheng as well. The influence on economic subsystem is quantified to 4.9, which is at a moderate level. As biogas slurry and residue serving as organic fertilizer could substitute the consumption of chemical fertilizer and increase the revenues of farmers, the impacts on consumption level and food production are the most prominent, with the value of 8.47 and 7.2. However, there is a minor influence on breeding industry in Gongcheng, which should be put into greater efforts in the future. The passive impact caused by the cost of biogas digester construction is relatively small with the value of −1.7, and by the government subsidy, this difficulty that farmers could not afford the construction cost could be gradually overcome.

The value of social benefit is calculated to be 4.4, which is between the slight and moderate level. The most significant influence on social aspect is the decrease in infection rate of intestine disease, which owns to the increase rate of excrements disposal. In addition, the application of biogas in rural areas cannot only increase employment opportunities and reduce emigration workers, but also make full use of rural surplus labor. Although the ratio of skilled farmer has increased by 30%, trainings need to be enhanced to cultivate "New Farmers."

Table 1 Evaluation indicator framework for biogas project

Destination layer	Criteria layer	Indicator layer	Explanation
Sustainable development	Environmental indicators	Increasing rate of organic matter	Increasing organic matter by returning biogas slurry, residue and straw to the field
		SO_2 reduction rate	Biogas as a substitution of coal to reduce SO_2 emission
		CO_2 reduction rate	Biogas as a substitution of coal and firewood to reduce CO_2 emission
		Forest deterioration reduction rate	Biogas as a substitution of coal and firewood to slowdown forest deterioration
		Proportion of arable land taken by biogasdigester	Arable land occupied by biogas digester construction
		Increase in animal excreta disposal rate	Improving residential environment quality through anaerobic fermentation
Sustainable development	Social indicators	Reduction in the rate of emigrate workers	More jobs and opportunities are provided by biogas projects
		Increase in labor productivity rate in rural areas	Surplus labor is fully used for maintenance of biogas digester
		Increase in the proportion of technical farmers	Enlarging the proportion of technical farmers through technical training on biogas technology
		Decrease in infection rate of parasitic disease	Influenced by the disposal of human and animal excreta
		Decrease in infection rate of intestine disease	Influenced by the disposal of human and animal excreta
	Economic indicators	Promotion in farmers' consumption level	Increase in income simulated the consumption
		Increasing rate of grain output per hectare	The use of organic fertilizer leads to the increase in grain output
		Increasing rate of pig breeding number	Biogas pool construction pulled the livestock breeding
		Increasing rate of fruit output per hectare	The developing mode of "pig-biogas-fruit" accelerated the development of fruit industry
		Proportion of construction cost	The proportion of pool construction costs in the whole expenditure

Table 2 Five-grade classification

Grades	Significant beneficial impact	Large beneficial impact	Moderate beneficial impact	Slight beneficial impact	Minor beneficial impact	Significant adverse impact	Large adverse impact	Moderate adverse impact	Slight adverse impact	Minor adverse impact
Rates	Increase by 90%	Increase by 70%	Increase by 50%	Increase by 30%	Increase by 10%	Decrease by 90%	Decrease by 70%	Decrease by 50%	Decrease by 30%	Decrease by 10%
Value	9	7	5	3	1	−9	−7	−5	−3	−1

Table 3 Impacts of biogas project on the sustainable development of agro-ecosystem

Destination layer	Criteria layer	Indicator layer	Total weight	Value of indicators	Value of impacts
Sustainable development	Environmental indicators 0.63	Increasing rate of organic matter	0.035	2.49	0.084
		SO_2 reduction rate 0.082	0.052	3.51	0.156
		CO_2 reduction rate 0.385	0.243	5.12	2.187
		Forest deterioration reduction rate 0.177	0.112	8.55	1.008
		Proportion of arable land taken by biogas digester0.029	0.018	0.54	–0.018
		Animal excreta disposal rate 0.272	0.171	7.8	1.197
	Social indicators 0.151	Reduction in the rate of emigrate workers 0.067	0.01	2	0.02
		Increase in labor productivity rate in rural areas 0.115	0.017	1.5	0.034
		Increase in the proportion of technical farmers 0.439	0.066	3.1	0.198
		Decrease in infection rate of parasitic disease 0.189	0.029	5.6	0.1624
		Decrease in infection rate of intestine disease0.189	0.029	9.1	0.261
	Economic indicators 0.218	Promotion in farmers' consumption level 0.059	0.013	8.5	0.104
		Increasing rate of grain output per hectare 0.282	0.06	7.2	0.42
		Increasing rate of pig breeding number 0.176	0.038	1.5	0.076
		Increasing rate of fruit output per hectare 0.443	0.097	5.5	0.485
		Proportion of construction cost 0.039	0.008	1.7	–0.016
Sum					6.3584

Table 4 Environmental, social and economic benefits derived from biogas project

	Environmental benefit	Social benefit	Economic benefit
Score	7.3	4.4	4.9
Level	Large beneficial impact	Moderate beneficial impact	Moderate beneficial impact

4 Conclusions

From a systematic perspective, a moderate beneficial impact is exerted on agro-ecosystem of Gongcheng, in which environmental factors contribute the most. For the environmental subsystem, the application of biogas has produced large environmental and ecological benefits, especially its significant role in decreasing the deforestation area, increasing animal excreta disposal rate and reducing CO_2 emission. There is also a promotion of economic subsystem by the utilization of biogas and its co-products, in which the impacts on consumption level and food production are the most prominent. However, the influence on breeding industry is relatively minor in Gongcheng, which should be put into greater efforts in the future. In addition, biogas project in rural area has either increased employment opportunities or reduced the incidence of diseases, thereby improving the social conditions in Gongcheng.

The evaluation system established in this study is useful to assess the contribution of the biogas project to rural sustainability. The developmental path of biogas and sustainable agro-ecosystem in the future could then be determined. As biogas could bring more benefits and fewer negative environmental impacts, the government should steadily propel the development of household biogas, and promote the food production and breeding industry to recycle the biogas residue.

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