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Microanalysis of the benefits of China's family-size bio-digesters☆

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ABSTRACT

The construction of 14 million family-size anaerobic bio-digesters is thought to have improved the farm economy of many rural households in China. The general view is that the use of a bio-digester will reduce expenditures on fuels and on fertilizers and pesticides, freeing up income that can be spent otherwise. The effect of using the residue of the digestion process is believed to increase farm produce also. Sound empirical support for these beliefs is, however, absent. Through the survey carried out for users and non-users in three villages (two in the Gansu province and one in the Sichuan province) it will be evident that the effects of the use of bio-digesters on the farm economy are often small if not non-existent. However, with appropriate support, the benefits can be significantly improved. Furthermore, the bio-digester contributes considerably to a more convenient lifestyle and an improved indoor environment. The benefits are not measured in terms of money, rather much appreciated by those who invested in a bio-digester.

1. Introduction

Just like many other developing countries China, also has a renewable energy program for its citizens residing in rural areas, which are often very remote. Within this program, many renewable energy technologies have been, and still are, developed to reduce the energy shortage that rural households face. An important renewable energy technology is the family-size anaerobic biogas digester, further denoted as bio-digester. Apart from reducing energy shortage, the bio-digester is also believed to alleviate poverty, since the use of the residue from the digestion process has a positive effect on farm production, and thus farm income. Furthermore, the bio-digester is also thought to improve the environment—indoors and outdoors. The indoors environment is enhanced by reduction in the incidents of illnesses from burning coal and firewood, and outdoors by reduction in carbon dioxide (CO_2) and sulphur dioxide (SO_2) emissions. In China's renewable energy program for rural areas, the anaerobic household or family-size biogas digester has played an important role from the commencement of the rural energy program. For decades, China has invested in bio-digesters, of which some 14 million were installed by 2005, producing some 3.5 billion m^3 of gas in total [1]. The potential contributions to energy production, poverty alleviation, and improvement of the environment of the biogas program have been reported many times in official documents, and have been described in several studies of rural energy technologies [2] and scientific articles [3–5].

Over the years, several models for household bio-digester applications have been developed. In the villages studied in this paper, the Three-in-One model, which stands for Pig-Biogas-Fruit/Vegetables, has been applied. A typical investment required for this model is in an anaerobic bio-digester, in combination with a new kitchen, pigpen, and toilet. The excrements of pigs and humans, in combination with fruit and/or vegetable residues are used as raw material in the bio-digester. The latter is 8–10 m^3 in size and produces between 0.3 and 0.9 m^3 of gas per m^3 digester per day. The bio-digester in terms of construction is relatively cheap (estimates range between Y 1500 (US$ 180) and Y 2200 (US$ 270)). It is simple to maintain, and has a long technical lifetime. The total investment required for the installation will depend on the investment model, but for the Three-in-One model the total investment cost can vary from Y 3600 (US$ 450) to as high as Y 6500 (US$ 820). This includes the cost of setting up the bio-digester, the renovation of the kitchen, the toilet, the pigpen, the water supply, and the courtyard [6].

An investment in a bio-digester is hardly ever an individual initiative. Normally a group of households belonging to a particular village invest in bio-digesters together. Such a project is mostly the result of marketing activities by the Rural Energy Office, eventually

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in collaboration with an NGO. The collective investment reduces costs through economies of scale. Within a project each household will get an investment subsidy, but will have to invest its own money also. The size of the subsidy will vary, depending on the economic conditions in the specific area.

Before a bio-digester is introduced, a household typically uses coal, firewood, and stalk and straw for cooking (and heating) purposes. In some households LPG is used, but always as a backup. The main benefits incurred from a bio-digester in relation to household income are the replacement of commercial fuels by biogas, the reduction in the time needed to collect firewood, and since fertilizer and pesticides can be (partly) replaced by the residue of biogas production, a reduction of the costs of these products. (For a brief discussion of the Chinese household size bio-digester see reference [7].)

The empirical support for the many benefits of household biogas digesters is, however, scarce. Only the improvement of the indoor environment has been investigated in detail [8,9]. Calculations of the financial benefits based on the empirical data are rare ([10,11]), and lack rigor. Much of the previous empirical research gives accounts of the energy effects of the use of biogas ([5,11,12]). Furthermore, during the many trips made by the authors of this paper to villages in China, it was difficult to get reliable confirmation on the benefits of bio-digesters from households that used it over a comparatively longer period of time. At a workshop held in Beijing on August 9, 2005 on renewable energy, it was reported by Sun Zhenqing of Tsinghua University, Beijing, who surveyed household bio-digesters in Hebei Province, that an estimated 70% of the bio-digesters constructed were still in place, and that only 30% were still used. Details of the survey were, however, lacking, and it is unclear why the digesters are no longer used. Was it due to malfunctioning and/or bad management, or were there other reasons; for example, the use of commercial fuels due to changes in the structure of the local economy? Therefore, further research is needed to clarify this issue.

The only way to collect reliable information on the use of bio-digesters and its benefits is by carried out surveys to study users and non-users of biogas that live under comparable circumstances. This research tries to fill the gap in the availability of reliable empirical information on bio-digesters and the role they play in farm economy by analyzing the similarities and differences between biogas users and non-users in three rural villages, Dong Yuan and Xia Ping in Gansu province, and Hua Niu in Sichuan province. The users in these villages invested in bio-digesters almost twenty years ago, and all are veteran users. As far as we know this is the first time that the benefits of the household bio-digester are analyzed in this way.

This paper is organized as follows. Section 2 discusses the range of benefits a rural household might have from investing in a bio-digester and introduces the villages surveyed. Section 3 analyses the actual benefits incurred by the households in the three villages by the use of a bio-digester by comparing the financial and non-financial differences among users and non-users in terms of farm income, energy use, and fertilizer and pesticide expenditures. Section 4 analyses the environmental benefits. Section 5 discusses the results, and uses these financial benefits to evaluate the investment in a bio-digester. Section 6 contains conclusions and suggestions for future research.

2. The contribution of the bio-digester to rural household income and spending

There are three areas in which a household bio-digester is thought to have a significant contribution. First of all it would free up part of a household's expenditure by reducing the expenditure on commercial energy, mainly coal, for cooking, and reduce the time needed to collect firewood. Second, the residue from the digestion process is a high quality fertilizer, and can also be used as a pesticide. So the use of the residue reduces expenditures on commercial fertilizers and pesticides, for which it is a (partial) substitute. Third, it is believed that the residue is actually a fertilizer of such a good quality that it will increase the production of vegetables, wheat, and fruits. Since the bio-digester is fed with pig manure, the income of users is expected to increase by raising (more) pigs also. Fourth, the use of a bio-digester has significant positive environmental effects. The indoor living conditions improve considerably after investing in a bio-digester, along with the accompanying investment in a new kitchen with the biogas cooking equipment, and an improved firewood cook stove, a pigpen, and a toilet. All this results in a very significant decrease in the emission of particles, which are thought to reduce illnesses related to indoor pollution [8,9]. Since the bio-digester qualifies as a renewable energy technology, and reduces the use of coal, it is thought to have a positive contribution to global emission reduction by reducing CO_2 emissions, as well as to the regional and local environment by reducing SO_2 emissions [13]. Furthermore, the use of bio-digesters reduces the uncontrolled disposal of annual and human excrements into the surface water. The next two sections will investigate if and to what extent are the advantages of household bio-digesters actually realized.

However, first it must be checked if there are significant differences between users and non-users, other than the use of bio-digesters in the three villages, as well as other kinds of differences there prevail among the villages.

2.1. The survey

The survey was carried out in January 2006, wherein 239 households were interviewed. It was conducted under the supervision of the Institute of Nuclear and New Energy Technology (INET) of Tshinghua University, Beijing, together with people from the local project offices of the Sino-Dutch Cooperative Project "Promotion of Rural Renewable Energy (RRE) in Western China". In each village, user and non-user households were surveyed. The total number of households in Dong Yuan village is 41, of which 27 invested in a bio-digester; in Xia Ping these figures are 56 and 29, respectively; and in Hua Niu 142 and 127. In Dong Yuan, the first digester was installed in February 1994, but the majority of the bio-digesters were installed between December 2002 and July 2004, so most users possessed more than two years of experience in bio-digester use. In Xia Ping, most of the digesters were installed in the first quarter of 2003, so at the time when the survey was carried out these users had more than two years of experience too. In Hua Niu, the first bio-digester was installed in October 1985 and the latest was finished just before the survey. Throughout the 1990s, as well as in the first half of this decade, households in Hua Niu invested in bio-digesters. However, the majority of the users possessed more than two years of experience, and 76 out of 127 had more than five years of experience. The population of the users consists of veteran users, which is important when empirically evaluating the benefits and drawbacks of bio-digesters.

It is to be noted that only four households that invested in a bio-digester stopped using it, two in Dong Yuan and two in Hua Niu. Given the age of some of the bio-digesters this is a remarkably low number. This finding indicates that the quality of the bio-digesters is good. This supports the belief, albeit empirically still unsupported, that households will only stop using their bio-digesters if they make enough money to pay for a more convenient commercial fuel, (eg., LPG, and live close to a town or city where LPG is readily available), or stop their farming activities because of changes in local economic conditions. However, further research is required to support this belief.

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2.2. One or three surveys: comparing villages?

The three villages show different characteristics, which makes it impossible to treat the data from the three villages as one big survey. They have to be analyzed as three separate surveys. For example, there are large and statistically significant differences in farm size between the three villages. With 9.38 mu (1 mu of land is approximately 1/15 of a hectare or 667 m^2) the average farm in Dong Yuan, Gansu province, is relatively large. Farms in Xia Ping (also Gansu) are on an average area of 4.88 mu, and farms in Hua Niu, Sichuan province, are on an average are of only 2.14 mu. These differences are, statistically, highly significant. To test this, SPSS was used to compare the means. First, Levene's test for equal variances was applied and then the independent samples *t*-test for equality of means.

Other important differences are the crops grown in each of the three villages. Where Dong Yuan shows a mix in gross farm income from fruits and annual crops (but less from breeding), fruits are the main crops grown in Xia Ping, and in Hua Niu, fruits and breeding are the main revenue earners; see Fig. 1.

Finally, the energy mix per village varies due to local conditions and farm activities. In Xia Ping, large amounts of firewood are used, because firewood is a by-product of the main farm activity, that is, growing fruit. Due to these (and other) important differences between the three villages, it is not possible to treat the survey as one, so each village must be analyzed separately.

2.3. Comparing users and non-users per village

In order to investigate the effects of the use of a bio-digester on a household's farm economy, the independent samples *t*-test is used to compare the means of the two groups, non-users and users, for those variables that are normally thought to be affected by the use of a bio-digester.

In order to draw conclusions on the effects of a household bio-digester in each of the villages, it must be ensured that the differences are not due to other factors. Therefore, the households that use a bio-digester (denoted as users) and households that do not use a bio-digester (non-users) in each of the three villages are compared using factors that are not related to bio-digester use. To see if user and non-user households can be compared and other factors can be ruled out, the differences between the two groups are tested using five variables: average number of persons per household, average number of persons that work, the area available for farm activities, the level of education of the head of the household, and non-farm income. If there are no significant differences between users and non-users with respect to these five variables, it is assumed that significant differences between users and non-users in the three main subjects of interest (spending on energy, pesticide and fertilizer, higher income from farming, and positive environmental effects) can be attributed to the use of the anaerobic bio-digester.

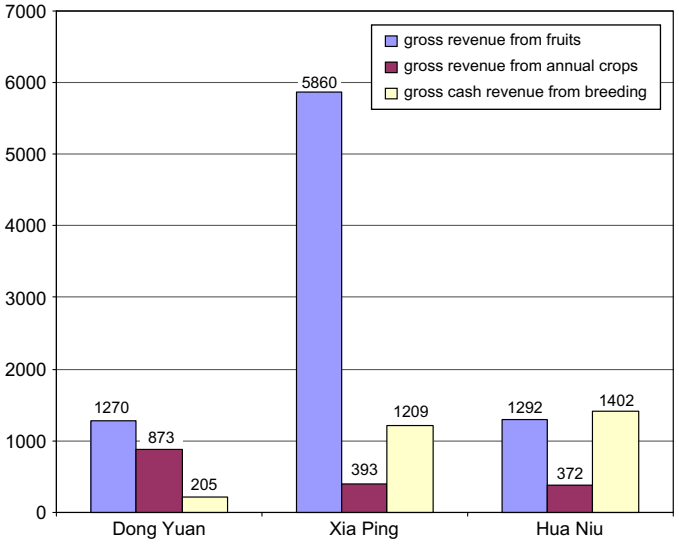

Fig. 1. Gross income from farming (fruits, annual crops and breeding) for the three villages.

Table 1 contains the results of the *t*-test. Given the relatively small size of sample, a significance level of $\alpha = 0.15$ was used. Table 1 shows that there is no significant difference in the average number of people per household with and without a bio-digester, in the average number of people working at the farm, and in farm size. In Dong Yuan, the difference in the average level of education of the head of the household is significant, but not in Xia Ping and Hua Niu. This education variable was included to see if better education leads to a different attitude towards new technology.

Since the investment in a bio-digester normally requires some private funding, non-farm income might be an important driver. The differences in non-farm income between non-users and users in each of the villages is, however, not significant, nor is the difference always in favor of the users. It is surprising to note that in all three villages the income from work other than farm work is considerable, showing that China's economic boom in the east has a profound effect on the rural areas in Sichuan and Gansu.

Despite the significant difference in the levels of education between users and non-users in Dong Yuan, it is concluded that there are no significant differences in the composition of user and non-user households in each of the three villages, nor in the way they earn their income. Therefore, differences in farm produce, fertilizer and pesticide expenditure, and energy consumption between users and non-users can be attributed to the use of the bio-digester. In the following sections it is analyzed if these differences do exist and are as expected from a theoretical point of view.

3. The effects of using a bio-digester

In this section, the differences between non-users and users for the three main income related areas affected by the utilization of a bio-digester are discussed. Sub-Section 3.1 discusses fuel use and expenditure; sub-Section 3.2 discusses the effect on the expenditure on fertilizers and pesticides; and sub-Section 3.3 analyzes if and how the bio-digester technology affects farm income.

3.1. Biogas and fuel use

To analyze similarities and differences in energy use between users and non-users, information on the use of firewood, stalk, coal for cooking and heating, and LPG was collected. LPG is used by 33 households (32 in Dong Yuan and 1 in Xia Ping), but always as a backup fuel. Biogas supposedly replaces the cooking fuels firewood, stalk, and cooking coal.

3.1.1. Fuel use

Table 2 shows that there are differences in the composition of fuels used among the three villages.

In Dong Huan, a mixture of stalk, firewood, and cooking coal is used, but only the difference in firewood use (507 kg/year against 154 kg/year; $p = 0.115$) is statistically significant. Although biogas users in Dong Yuan use 388 kg/year less stalk (on average non-users use 1189 kg/year), and 137 kg/year less cooking coal (non-users use 289 kg/year), these differences are not statistically significant.

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Table 1
Comparing users and non-users.

		Dong Yuan		Xia Ping		Hua Niu	
		Mean	2 tailed test	Mean	2 tailed test	Mean	2 tailed test
Number of persons per household	Non-users	5.14	0.501	4.89	0.821	3.93	0.451
	Users	4.89		4.82		4.19	
Number of persons that work	Non-users	2.36	0.679	2.43	0.405	2.53	0.205
	Users	2.48		2.64		2.89	
Area available for farm activities in mu	Non-users	9.38	0.995	4.85	0.853	2.29	0.248
	Users	9.37		4.91		2.12	
Level of education of the head of the household[a]	Non-users	2.29	0.061	2.71	0.411	2.20	0.658
	Users	2.74		2.89		2.35	
Non-farm income (Yuan per year)	Non-users	2786	0.715	2878	0.883	6867	0.564
	Users	2381		3000		7789	

[a] 1 = illiterate, 2 = primary school, 3 = junior high school, 4 = senior high school, and 5 = junior college.

In Xia Ping, none of the differences in fuel use are significant, with the exception of stalk, but in that too users actually use more stalk, not less, than the non-users do. The bio-digester seems to have no effect on fuel use for cooking. Non-users and users alike use large amounts of firewood, which is a by-product of their main agricultural activity, growing fruit. This is reflected by the relatively small amount of stalk used.

In Hua Niu, there is a significant difference in the amount of coal used for cooking, 793 kg/year by non-users against 287 kg/year by users ($p = 0.019$); see Table 2.

Biogas might be used for heating also. Therefore, the differences in the average amount of coal used for heating are tested; however, these were not in a significant amount.

Remark: Using less firewood is thought to be an important contribution of bio-digesters to the improvement of the farm economy, because it is assumed that collecting firewood takes a lot of time and leads to deforestation and soil erosion. This is, however, only a viable assumption when firewood is not a by-product of farm activity, as is the case in Xia Ping.

3.1.2. Electricity use

Biogas is supposedly also used for lighting, and many biogas investment projects include the installation of gas lamps. However, the villages do have electricity, as do almost all villages in rural China; therefore biogas is hardly used for lighting. As shown in Table 2 there are no significant differences in electricity use between non-users and users. This is in accordance with the findings of Xiaohua et al. also [11].

3.1.3. Expenditure on fuels

Although the examined households were able to ascertain the expenditure on coal, yet unable to distinguish between expenditures on cooking coal and coal for heating. The spending on these two categories has been calculated using the amount of coal used for cooking (which is easy to distinguish since it has a special honeycomb-like shape to fit into the widely used coal cooker), multiplied by the price of this coal in each of the three villages. The expenditure on coal for heating was obtained by subtracting this amount from the total expenditure on coal.

Given the limited substitution effects of biogas and other fuels, it is not surprising that the effects on energy expenditures are also limited; see Table 3. The annual savings incurred by users on the expenditure on cooking coal are Y 39 (US$ 5) in Dong Yuan (Y 82 versus Y 43), Y 2 in Xia Ping, and Y 141 (US$ 18) in Hua Niu. Only in the latter case is this difference in spending between non-users and users significant ($p = 0.019$).

The effect of biogas on expenditures for cooking and electricity is limited and mainly not significant, yet it is still interesting to test whether biogas does have any effect on the total expenditure on energy. Although spending for each fuel separately is not significant, in Table 3 it is shown that the spending on each fuel separately by users is generally less than by non-users. Furthermore, a number of households also use other fuels, such as LPG, for cooking. The use of biogas might result in less expenditure on energy, and that is quite significant at the aggregate level. However, diesel and gasoline are excluded, since only a limited number of households use these fuels for transport and the use of machinery, not for cooking or heating. As the last entry in Table 3 shows, there is a significant effect on the expenditure on cooking and heating in Dong Huan (Y 213/year (US$ 27) against Y 128/year (US$ 16); $p = 0.089$). This can most likely be attributed to a reduction in LPG use. Also, in Hua Niu the difference is significant (Y 309/year (US$ 39) against Y 156/year (US$ 20); $p = 0.011$), but here the reduction in spending on cooking coal was already significant.

3.2. Fertilizer and pesticide use

Another important advantage attributed to the use of a bio-digester is the replacement of nitrogen fertilizers and pesticides by the residue of the digestion process. If the anaerobic process works

Table 2
Annual consumption of energy by users and non-users.

Kg per year		Dong Yuan		Xia Ping		Hua Niu	
		Mean	2 tailed test	Mean	2 tailed test	Mean	2 tailed test
Stalk consumption	Non-users	1189	0.217	252	0.125	687	0.865
	Users	801		405		729	
Firewood consumption	Non-users	507	0.115	2181	0.234	280	0.751
	Users	154		2219		324	
Cooking coal	Non-users	289	0.171	433	0.588	793	0.019
	Users	152		386		287	
Heating coal	Non-users	210	0.311	54	0.271	170	0.531
	Users	137		78		102	
Electricity	Non-users	203	0.998	321	0.420	234	0.345
	Users	204		361		313	

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Table 3
Annual expenditure on energy by users and non-users.

Yuan per year		Dong Yuan		Xia Ping		Hua Niu	
		Mean	2 tailed test	Mean	2 tailed test	Mean	2 tailed test
Expenditure on heating coal	Non-users	128	0.304	34	0.686	54	0.570
	Users	83		47		33	
Expenditure on cooking coal	Non-users	82	0.171	126	0.601	221	0.019
	Users	43		122		80	
Expenditure on electricity	Non-users	99	0.988	157	0.548	187	0.345
	Users	100		177		250	
Expenditure on cooking and heating	Non-users	213	0.089	164	0.957	309	0.011
	Users	128		162		156	

well, the residue is a first class fertilizer; and if used correctly it can also replace some of the pesticides. If these effects materialize, one would expect that the expenditure on fertilizers and pesticides by users would be significantly less than by non-users. As shown in Table 4, this effect is absent. There are significant differences in the expenditure on pesticides in Xia Ping (Y 307 (US$ 39) by users and Y 216 (US$ 27) by non-users; $p = 0.074$) and Hua Niu (Y 254 (US$ 32) against Y 123 (US$ = 15); $p = 0.059$), but the users spend significantly more, not less, on pesticides. In Hua Niu, users spend significantly more (Y 627 (US$ 79) against Y 335 (US$ 42); $p = 0.022$) on fertilizers also.

The absence of a significant effect on pesticide and fertilizer use points to a fundamental problem in the organization of the dissemination process of the bio-digester technology. It is treated too much as a renewable energy technology, whereas its function as a technology for the production of fertilizers and pesticides is treated as insignificant or just an afterthought. Although the farmers do get some explanation on the use of these products, this aspect is not well understood, neither by the local Rural Energy Office that supervises most of the bio-digester implementation projects, nor by the technicians that construct the digester and offer some simple explanation at the end of the construction. For the bio-digester technology to be successful as a tool for improving farming, its role in the farm economy has to be analyzed properly, taking into account the local conditions. The current practice is a brief introduction in the use of the residue, but farmers need much better and longer-term support to realize these benefits. This present survey shows that the farmers use the residue as just a fertilizer and pesticide, but not as a replacement. It is applied by users together with more commercial pesticides and fertilizers than applied by non-users, instead of replacing these.

3.3. Effect of biogas on income

It is seen that just potential substitution effects were analyzed in the above sections, where the expenditure on fuels used for cooking and heating, and electricity purposes, and on fertilizers and pesticides were replaced by the output from biogas production. These effects will not increase the income of the users, but may potentially free up money and time that can be spent otherwise. As seen above, these effects are either small (in fuels), absent (in electricity), or opposite (in pesticides and fertilizers) to the claims made in the theoretical literature. Another important claim has always been that the introduction of a bio-digester will lead to an increase in income, because of the positive effects it will have on agricultural production. These effects on income are analyzed in this study.

Before this effect can be analyzed, a problem must be resolved. Most farms in China are small, and the household itself consumes a large part of the output. As a result the net revenue from selling agricultural products cannot be calculated by subtracting the cost of production from cash income from farming, since a substantial part of the spending on seeds, fertilizers, pesticides, etc., is actually spent on the production for an individual's personal use. There are two ways to tackle this problem. Either (1) the amount for personal use is valued at the market price and this is added to the actual cash sales to estimate total income, or (2) calculate the share of total produce that was sold and than distribute the costs according to this ratio over personal use and sales. The net revenue is than estimated as gross sales minus its share in total expenditures for agriculture. From an economic theoretical point of view, valuing the personal use against market prices is preferred, since the household has had the opportunity to sell all its products. In total, 17 different products were encountered, including rice, corn, and wheat, a wide variety of fruits, and an even wider variety of vegetables. The local market prices for these products are, however, not recorded, but the average market price of a product can be estimated by taking the average of the sales value divided by the quantity sold overall households that sold the product. Unfortunately, for several products the quantities sold are small, so the estimates of these market prices may be unreliable. This inaccuracy of data estimation favors the use of the share of sales in total production. The recollection of the interviewees of the amount of money spent on fertilizers and pesticides for each of the products may, however, not be too reliable either, apart from the fact that vegetables, for example, are grown together. For empirical reasons neither of the two methods seems superior to the other. Therefore, both results are presented here. If they work well the qualitative conclusions will be the same.

Another potential source of income due to the introduction of a bio-digester on a farm is breeding pigs. The present survey contains information on cash income from selling pigs. However, a substantial part of the pigs are used for private consumption. The market price of a pig in the three villages is estimated in the same way as the

Table 4
Expenditure on fertilizer and pesticide.

		Dong Yuan		Xia Ping		Hua Niu	
		Mean usage	2 tailed test	Mean usage	2 tailed test	Mean usage	2 tailed test
Expenditure on pesticide (Yuan/year)	Non-users	131	0.200	216	0.074	123	0.059
	Users	182		307		254	
Expenditure on fertilizer (Yuan/year)	Non-users	431	0.975	645	0.569	335	0.022
	Users	428		728		627	

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one employed for the price of vegetables and fruits. In this way, the value of the gross cash income from breeding is calculated. (It is to be noted that it is assumed that the price would not be affected by additional sales.) Unfortunately, no information on the cost of breeding pigs (or other animals) is available. Experts present anecdotal information that the profit per pig is between Y 100 and Y 150, but this information is not used to estimate the additional net income from pigs. Rather, for analyses carried out in this paper, the gross income from breeding is reported. It is to be noted that this includes income from poultry also; however, this income is rather small compared to that incurred from breeding pigs.

It is seen from Table 5 that only in Hua Niu is the difference in gross cash income from agriculture of Y 1083 (US$ 136) (Y 1778 (US$ 224) versus Y 695 (US$ 87); $p = 0.035$) between users and non-users significant. Can this difference be attributed to the use of a bio-digester? Since in Hua Niu the users used significantly more commercial fertilizers and pesticides than non-users do, the difference cannot be attributed to the use of a bio-digester. Using the net income does not change the results. When using market prices to determine the value of personal use, the differences in average net income are not significant. In Hua Niu, the difference in net income from the agriculture based on the personal use cost ratio is significant, but the difference of Y 741 (US$ 93) (Y 472 versus Y 1213; $p = 0.085$) is smaller than the difference in gross cash income (Y 1083).

The effect of breeding is small. It is only in Xia Ping that the difference in average gross cash income of Y 419 (US$ 53) from breeding is found to be significant ($p = 0.110$); see Table 5. If the use of pigs for personal consumption is valued at market prices, the differences between users and non-users in Dong Huan and Xia Ping remain insignificant, but in Xia Ping it remains significant and increases to Y 934 (US$ 118) (Y 1837 (US$ 231) for non-users against Y 2771 (US$ 349) for users; $p = 0.011$).

The differences in income from breeding between the villages are remarkable to note; see Table 5. This can be explained by the large differences in the number of pigs kept for breeding purposes. In Dong Huan, the farmers keep only 1.1 pigs on an average, in Xia Ping 2.2, and in Hua Niu 3.2 pigs, but only in Xia Ping is the difference between non-users (1.7 pigs) and users (2.7 pigs) significant enough to note ($p = 0.004$). The causes for the difference in the number of pigs per village are unclear, given the fact that the bio-digester requires the manure of 2–4 pigs. In Dong Yuan, some farmers mentioned the fact that the net revenues from pig breeding are insufficient, but the survey contained no questions on this subject.

Although most of the differences in gross cash income from agriculture and breeding are not significant, yet their combined effect might be. Therefore, the average difference in gross cash income has been tested also; however, in none of the villages was this difference significant; see Table 5, in the Total gross cash income row. It is to be noted, however, that the average gross cash income of users in each of the villages is larger than that of non-users. The conclusion from this analysis can only be that from a statistical point of view, the overall income effect of a bio-digester is weak, if not absent.

3.3.1. Other benefits

Apart from the benefits mentioned above, the use of a bio-digester is thought to have other benefits too, such as saving time spent on collecting firewood and stalk, cooking, and housework in general. As seen in Table 6, the time saved on collecting firewood and stalk is not significant, even in Dong Huan where the time saved is 16.9 days per year. In Xia Ping, the difference is very small, but this is due to the fact that firewood is a side product of the main farming activity, that is, growing fruits.

The time per day saved on cooking is between 20 (in Hua Niu) and 40 min (in Xia Ping), and it is significant in Dong Hua ($p = 0.050$) and Xia Ping ($p = 0.019$). The time spent on housework per day is very similar in the three villages, but only in Xia Ping is the difference between non-users and users (4.9 h versus 4.2 h; $p = 0.150$) significant enough to note.

The analysis carried out in this present study shows that the positive effects a bio-digester supposedly has on a farm are to a large extent not supported by our empirical findings. The savings in fuel cost, expenditure on fertilizers and pesticides, as well as higher produce are insignificant from a statistical point of view, and rather limited in financial terms. Furthermore, the results show that the farmers are unaware of the appropriate use of the bio-digester technology, despite the fact that most are veteran users.

4. Bio-digesters and the environment

A bio-digester has a positive effect on a household's indoor living conditions due to the accompanying investment in a new kitchen with biogas cooking equipment and an improved cook stove, a pigpen, and a toilet. As was shown by Sinton et al. [8] and Zhang and Smith [9] this results in a very significant decrease in the indoor emission of particles, and thus reduces illnesses related to indoor pollution. Because a bio-digester treats manure in a closed system, it considerably reduces the number of insects found indoors also. However, the empirical proof for the effects on health is still lacking since this would require long-term (spanning 10 years or more) and continuous examination of health statistics of the family members of many rural households. A one-time survey cannot be used to empirically support claims on improved health. Furthermore, for this research no health checks of the members of

Table 5
Annual income and expenditure.

Yuan per year		Dong Yuan		Xia Ping		Hua Niu	
		Mean	2 tailed test	Mean	2 tailed test	Mean	2 tailed test
Gross cash income from agriculture	Non-users	1664	0.287	5805	0.425	695	0.035
	Users	2393		6671		1778	
Net income from agriculture using market prices	Non-users	2855	0.895	6514	0.669	1698	0.493
	Users	2950		6994		2040	
Net income from agriculture using private use ratio	Non-users	1264	0.263	4978	0.537	472	0.085
	Users	1979		5662		1213	
Gross income from breeding	Non-users	158	0.580	992	0.110	1585	0.597
	Users	229		1411		1380	
Gross income from breeding using market prices	Non-users	685	0.293	1837	0.011	3565	0.677
	Users	909		2771		3301	
Total gross cash income	Non-users	1822	0.285	6797	0.269	2280	0.241
	Users	2622		8081		3158	
Total expenditure for agriculture	Non-users	712	0.661	1018	0.594	566	0.008
	Users	779		1129		1051	

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Table 6
Other benefits.

		Dong Yuan		Xia Ping		Hua Niu	
		Mean	2 tailed test	Mean	2 tailed test	Mean	2 tailed test
Time spend on collecting firewood and stalk (days per year)	Non-users	30.4	0.231	16.9	0.875	12.7	0.326
	Users	13.5		17.7		9.5	
Time spend on cooking (hours per day)	Non-users	3.04	0.050	2.70	0.019	2.93	0.332
	Users	2.50		2.08		2.55	
Time spend in housework (hours per day)	Non-users	5.71	0.794	4.91	0.150	5.73	0.247
	Users	5.57		4.24		5.15	

the user and non-user households were performed. The only contribution this research can give is based on the survey question, "Do you think the health of your family members has improved?" Fig. 3 shows that the majority of users (99 of a possible 178) responded that it improved a great deal, 55 responded that it is better, and only 6 believe there is no difference.

Since the bio-digester is a renewable energy technology and, among others, reduces the use of coal, it should, when used properly, contribute positively to global emission reduction. To calculate this environmental effect, the energy savings in terms of standard Chinese coal equivalent (kgce) have been calculated; see Table 7. As concluded before, the savings per village per fuel show large differences. In Xia Ping the use of the bio-digester seems to have no effect on energy use, but in Dong Hua 517.6 kgce of primary energy is saved per household (104 kgce/capita), and in Hua Niu 335.6 kgce (80.7 kgce/capita). The overall difference in primary energy use between non-users and users is 230.2 kgce, which is of course the best estimate available for the total effect of the bio-digester on other energy use. When only considering coal, users in Dong Huan consume 149.9 kgce less, in Xia Ping only 16.4 kgce, and in Hua Niu 409.8 kgce. On an average, users consume 165.6 kgce/year less coal than non-users. These reductions are considerably lower than those found by Xiaohua et al. [11]. They conclude that the difference in energy use between users and non-users is 133 kgce/capita/year in Liangshui and 155 kgce/capita/year in Guichi, which is considerably higher.

The environmental effect of a bio-digester is mainly due to its reduction in coal use. On an average the Chinese coal used has a heating value of 20.934 MJ/kg, and contains 24.74 ton C/TJ and 14.08 kg SO_2 per ton of coal. The savings in use of coal as shown in Table 7 result in an average annual reduction in CO_2 and SO_2 emissions per household of 77.65 kg C, and almost 2.11 kg of SO_2 in Dong Huan, and 212.26 kg C and 5.77 kg SO_2 in Hua Niu. Because the savings in the use of coal in Xia Ping are virtually absent, the emission effects can be neglected (8.55 kg C and 0.23 kg SO_2). On an average, this results in a reduction of 85.79 kg C and 2.33 kg SO_2 per household for the three villages combined, due to a reduction in use of coal.

One could argue that less firewood and stalk is used due to the use of biogas, reducing emissions also. However, this depends on what the alternative use for these products is. In case firewood and stalk is available anyway, and there is no alternative use, it is a standard practice that they are burned in the field or near the fruit yard. Further research on this subject is needed regarding this aspect before any conclusions can be drawn.

There is one final aspect of biogas usage that reduces the outdoor environmental effect of bio-digesters, considerably. Forty-three users stated that in the summer more biogas is produced than is actually needed. Most users emit this biogas into the atmosphere, only four users use combustion to get rid of the excessive gas. Since the useful part of biogas is CH_4 (50–70%), which is 21 times more polluting than CO_2, emitting biogas into the atmosphere will offset

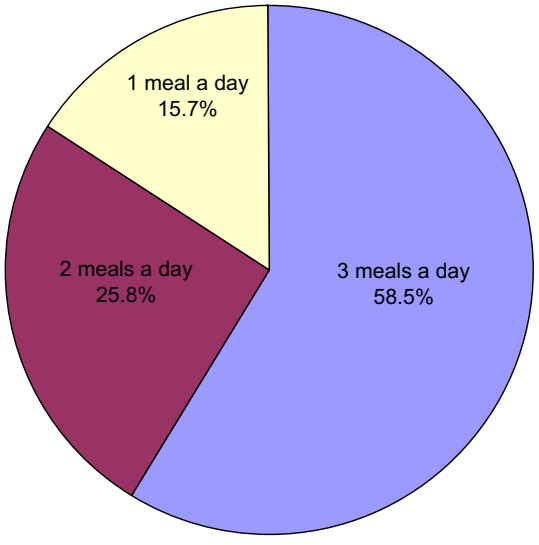

Fig. 2. The total number of meals that can be cooked per day using biogas for all the three villages.

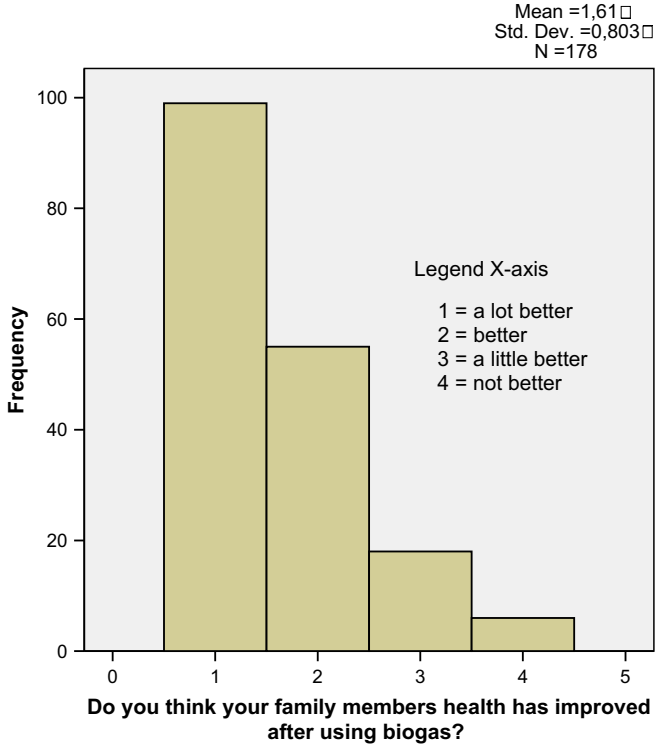

Fig. 3. The users perception of improvement due to the family-size bio-digester.

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Table 7
Energy savings in kg coal equivalent.

Fuel	Conversion to kgce[a]	Dong Yuan	Xia Ping	Hua Niu	Weighted average
Stalk	0.429	166.5	−65.6	−18.0	−18.9
Firewood	0.571	201.6	−21.7	−25.1	97.6
Electricity	0.392	−0.4	−15.7	−30.9	−14.2
Coal	0.714	149.9	16.4	409.8	165.6
Primary energy		517.6	−86.6	335.8	230.2

[a] The conversion factors used are based on [13].

the positive environmental effects of a bio-digester considerably. Unfortunately, the actual year-round data on biogas production and usage in the three villages are not available, so the size of this effect cannot be quantified. For this, more detailed and long-term research is required. It is to be noted that emission of CH_4 will occur only when there is sufficient gas to cook at least three meals a day using biogas, which is on average 58.5% of the time; see Fig. 2.

Finally, the use of bio-digesters reduces the uncontrolled disposal of annual and human excrements into surface water. The survey did, however, not contain any questions on this effect.

5. Discussions

The effect on farming, fuel use, the environment, and household income of the bio-digester technology has been analyzed empirically by comparing farm produce and income, and expenditures on fertilizers, pesticides, and fuels by users and non-users. Although the expanse of the survey is rather small and the results cannot be generalized due to the large differences across China in local conditions and variations in bio-digester application model, the research results give some cause for alarm. The many benefits that are attributed to the use of an anaerobic bio-digester have been realized only partly at the most, despite the fact that the users in the survey are regarded as veteran users, one would expect to be knowledgeable in the utilization of the bio-digester technology and its output.

As shown above, the replacement effect of cooking coal and firewood/stalk by biogas is very limited, and in one village, Xia Ping, even absent, and so are the savings in terms of money spent on energy.

For 2005, Yu et al. [14] calculated a substitution of 135,252 TJ of fuels by biogas, resulting in GHG emission reduction of 14,410 Gg CO_2-equivalent. The analyses carried out in the present study show considerably lower savings in the use of coal and other fuels than previously assumed, that is up to 75% less, thus, reducing the estimated GHG emission reduction considerably. However, the scope of our research is too limited, both geographically and in size, to calculate reliable nation wide effects. However, it does provide reasons for concern.

The utilization of the residue of the anaerobic digestion process in combination with commercial fertilizers and pesticides shows that this aspect of the technology is not well understood by the farmers. There has been no substitution between residue and commercial fertilizers and pesticides; on the contrary, the bio-digester users often use more instead of less commercial fertilizers and pesticides than those used by non-users. This also shows that the claim made by Chinese researchers, that the introduction of a bio-digester on a farm results in production of farm products that can be viewed as biologically healthy products, is actually not supported by facts. The only conclusion that can be drawn here is that the role a bio-digester is intended to play in farming is not taught properly to the farmers. In many cases, it is the technician that constructs the bio-digester who teaches the farmer about residue use. These technicians are, however, not farming experts. Thus, a better understanding of this technology by farmers is needed. This can only be achieved by better and longer-term support from farming experts when introducing bio-digesters in an area.

The indoor environmental effects have been analyzed in detail by other researchers. The only contribution that the authors of this study can make to the study of these effects is to provide information that most interviewees perceive an improvement in the health status of their families that they attribute to the use of the bio-digester. Although the difference in the average use of coal is only statistically significant in Hua Niu (see Table 2), the use of cooking coal by users is smaller in each of the three villages, and the overall reduction is significant too. So the claim that the use of bio-digesters reduces greenhouse gas emissions is supported by results given in this present study, but the findings of this paper show a smaller effect than stated by others [11].

Since the subsidy on a bio-digester does by no means cover the investment cost, a household normally has to contribute a significant amount of money to it. So if the benefits of a bio-digester are small, why do households still invest in it? The authors of the present study gained the impression that an important reason for this is the fact that the investment in the bio-digester is combined with a major renovation of the farm (at least a new kitchen, pigpen, and toilet). The renovated farm is much more pleasant to live in. This convenience argument is reflected in the survey conducted by this study by the fact that the wife and grandparents are seen as the major beneficiaries of the investment.

The bio-digester investment projects are said to aim at helping the very poor. However, the average money income in the three villages is relatively high: Y 4868 (US$ 612) in Dong Huan, of which 52% comes from non-farm activities. In Xia Ping this is Y 10,403 (US$ 1309) and 28%, and in Hua Niu Y 10,756 (US$ 1353) and 71%. In terms of purchasing power these incomes have to be multiplied by a factor 2 at least, so in terms of purchasing power the households in the three villages are relatively well off. Furthermore, a considerable part of their money income is generated from activities other than farming. On the basis of this money income, the households grow and breed the majority of their own food.

The fact that the wife and the grandparents are seen as the main beneficiaries of the renovations that accompany the investment in a bio-digester, and the fact that a substantial part of the money income is from work other than farm work, suggests that the households regard the renovations and the improved indoor living conditions as the major benefits, and not the financial benefits discussed above. However, further and more varied research is needed to investigate this aspect.

5.1. NPV analysis

The question that now arises is, "Why do all investment proposals conclude that investing in a bio-digester is profitable?" To answer: The benefits (although not statistically significant) that

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Table 8
Review of the financial benefits in Yuan per year.

	Dong Yuan	Xia Ping	Hua Niu
Savings on energy expenditure for household activities	85	21	89
Savings on expenditure for nitrogen fertilizer and pesticides	−48	−174	−423
Operation and maintenance costs	37	37	37
Increase in gross cash farm income	800	1284	878
Total benefits without fertilizer and pesticides	885	1305	967
Total benefits	837	1110	544

result from the average differences in farm income, and expenditures on fuels, and fertilizer and pesticides, between users and non-users can be used to evaluate the investment in a bio-digester. The difference in the average expenditure on energy required for household activities is taken as an indication of the effect of the bio-digester on energy spending. This effect is small and non-significant; see Table 8, first row. As shown above, there are no savings on expenditure for nitrogen fertilizers and pesticides in the three villages; actually the users spend more, not less, than non-users do. Although not significant, yet the gross cash income from farming activities (crop growing and breeding) by users is seen to be larger than that of non-users in each village; see Table 8, fourth row. This present survey contains some information on operation and maintenance costs also. In Hua Niu, this amount is the largest, Y 37/year, and it will be used in the calculations for each of the villages. Next is the calculation of the net benefits with and without fertilizers and pesticides; see the last two rows of Table 8.

It is now assumed that these benefits are realized each year. Although it is realized these differences between users and non-users are not statistically significant, yet they can still be used to indicate the NPV of the investment in a bio-digester. The investment costs are, depending on the local conditions, estimated to be between Y 3483 (US$ 438) and Y 4580 (US$ 576); the simple payback period then varies between 4–8 years and 5–10 years, respectively. If the negative effect of the expenditures on fertilizer and pesticides are discarded, the simple payback periods reduce to 4–5 and 4–6 years, respectively. In case of a discount rate of 10% and an evaluation period of 15 years, the NPV for Dong Huan ranges from Y 1505 to Y 2607, for Xia Ping from Y 3422 to Y 5482, and for Hua Niu from minus Y 724 to Y 3231. These results show why in many cases, despite the fact that the differences between users and non-users are not significant, it is concluded that the investment in a bio-digester is profitable.

6. Conclusions

The net benefits of bio-digesters are considered to significantly contribute to farm income in China's rural areas, when compared to non-users. By surveying users and non-users that otherwise live under similar conditions in three villages (Dong Huan and Xia Ping in the Gansu province and Hua Niu in the Sichuan province), it was shown that the empirical support for this claim is missing. The differences in the money saved on energy expenditures are small and non-significant. The savings on fertilizers and pesticides are absent; users actually use more of these products than non-users do. Finally, the increase in farm income is not significant and cannot be attributed to the use of the bio-digester. However, the overall benefit is positive in each of the villages. If the investment in a bio-digester is evaluated using these non-significant differences in average benefits, the NPV is in most cases positive. What was shown here is that the effects of the bio-digester on income from farming are actually small, and as a result the bio-digesters' effect on poverty alleviation is also small. However, the importance of conducting more research, spread over a wider geographical area is needed to validate the results presented here has to be realized.

Apart from the financial benefits incurred, a bio-digester has indoor and outdoor environmental benefits too, on which a money value could not be put. The improvement in living conditions that results from the renovations of the kitchen, pigpen, and toilet, is highly appreciated. As a result, the people who spend most time in and around the house are seen as the main beneficiaries of the investment. Furthermore, almost all interviewees linked the improvement of the indoor environment to a reduction in the occurrences of illnesses. Together with the fact that the households that invest are not necessarily the poorest, this suggests that the investment might be appreciated more as an investment in convenience and improved living conditions, than as an investment in improved farming. However, further research is needed to substantiate this.

It is found that the contribution to emission reduction is also limited. There is some reduction in the use of cooking coal, but only in one village is this difference statistically significant. The reduction in use of fuel found here is smaller than the differences found by others. Overall there is, however, a significant difference in coal use, which results in some reduction in CO_2 and SO_2 emissions, but potentially up to 75% less than previously assumed.

What needs to be investigated in more detail is why the benefits in terms of fertilizer and pesticide replacement are not realized. This research suggests that a bio-digester is mainly seen as a renewable energy technology, and that its role as a technology to produce fertilizer and pesticide substitutes is insufficiently appreciated. Although farmers get information on how to use the residue, the effects this has on farm economy need to be analyzed in more detail. Currently, only a very general and technical explanation on how to use the residue is provided to the farmers. This needs to be improved, and the utilization needs to take into account local farming conditions. Only then will residue utilization be fully realized and thus result in improved products at lower costs.

Another important question to be pondered over is: Does this mean that China's bio-digester policy has failed? The answer: Of course not, this research has only shown that the benefits of this policy so far might be less than generally assumed, and rather it reveals that an improvement is required in the dissemination policy of the bio-digester technology in order to better realize its many benefits.

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