# Supplementary Materials: Greenhouse Gas Mitigation of Rural Household Biogas System in China: A Life Cycle Assessment

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## 1. Method to Calculate GHG Mitigation

We established a LCA model to calculate GHG (greenhouse gas) mitigation of Chinese RHB systems, comparing RHB households with non-biogas households, and studying the single household level (Figure 2 in main manuscript).

### 1.1. Net GHG Balance

GHG mitigation from RHB, $R_h$ can be summarized as follows:

$$R_h = (E_t + E_m + E_r) - (E_f + E_l)$$

where, $R_h$ is GHG emission mitigation by RHB, in kg $CO_2$-eq. $E_t$ is GHG emission mitigation of biogas by replacing traditional energy, in kg $CO_2$-eq. $E_m$ is GHG emission mitigation of manure storage by RHB vs. counterfactual manure storage, in kg $CO_2$-eq. $E_r$ is the GHG mitigation from nutrients replaced by biogas residue, in kg $CO_2$-eq. $E_f$ is GHG emission from its construction, in kg $CO_2$-eq. $E_l$ is GHG emission for the gas leakage, in kg $CO_2$-eq.

### 1.2. GHG Emissions from Construction

Cement and solid bricks are the two main raw materials used for biogas facility construction. Two published studies have estimated the GHG emissions associated with cement and clay brick production and transportation in China, using life cycle assessment [1,2]. We cited their results and calculated the GHG emission from RHB tank construction in two villages by Equation (S1).

$$E_f = 1026.2 \times C + 0.72 \times Br \tag{S1}$$

where, $E_f$ is GHG emission from RHB tank construction, in kg $CO_2$-eq. 1026.2 is GHG emission from cement production, in kg $CO_2$-eq·$t^{-1}$ (data from Gong [1]). And 0.72 is GHG emission from solid brick production, in kg $CO_2$-eq per standard brick (data from Luo [2]). $C$ is cement amount used for biogas construction, in t. And $Br$ is the number of bricks used for biogas construction, in standard brick (240 × 115 × 53 mm).

### 1.3. GHG Emissions from Manure Storage

$CH_4$ emissions from manure storage in biogas digesters or lagoons were calculated using a modified Tier 2 method from IPCC (2006).

$$CH_{4E} = (M \times dm) \times [B_o \times 0.67 \times \sum \frac{MCF}{100}]$$

where, $CH_{4E}$ is $CH_4$ emission of manure storage, in kg. $M$ is fresh manure quantity injected into RHB, in kg (survey data). $dm$ is dry matter content of manure, in % (Table S6). $B_o$ is $CH_4$ yield potential of dry matter of manure, $m^3$·$kg^{-1}$ dry matter, and 0.67 is conversion factor of $B_o$, in kg·$m^{-3}$ (data from IPCC 2006). $MCF$ is transform factor of $CH_4$ under the different management style, in % (i.e., stack and lagoon) (Table S2).

Nitrogen emitted to air in the forms of $N_2O$ and $NH_3$, or losses to water bodies as $NO_3^-$ during manure storage, are other important direct and indirect contributors to GHG emissions. The latter two can finally convert to $N_2O$ through series of process (i.e., leaching, ammonia volatilization and N deposition)—so called indirect $N_2O$.

Direct $N_2O$ emission ($N_2O_D$) and indirect $N_2O$ ($N_2O_G$) from $NH_3$ and $NO_3^-$ were calculated as follows.

$$N_2O_D = M \times f_{MN} \times EF_s \times \frac{44}{28}$$

where, $N_2O_D$ is direct $N_2O$ emission, in kg. $M$ is manure quantity injected into biogas digester, in kg (measurement data from this research). $f_{MN}$ is N content in manure (test data from this research, in %, Table S6). $EF_s$ is direct emission factor in manure management system S, in kg $N_2O$-N $kg^{-1}$ dry matter (Table S2). 44/28 is $N_2O$ emission from $N_2O$-N (IPCC, 2006).

$$N_2O_G = \left(M \times f_{MN} \times \left(\frac{Frac_{GasMs}}{100}\right) \times EF_4\right) \times \frac{44}{28}$$

where, $N_2O_G$ is indirect $N_2O$ emission in manure management, in kg $CO_2$-eq. $M$ is manure quantity injected into biogas digester, in kg (measurement data from this research). $f_{MN}$ is N content in manure (test data from this research, in %, Table S6). $Frac_{GasMs}$ is the ratio of $NH_3$ and $NO_X$ as emission form in manure management S, in % (Table S2). $EF_4$ is emission factor of $N_2O$ in soil and N deposition, in kg $N_2O$-N $kg^{-1}$ ($NH_3$-N + $NO_X$-N volatilization) (Table S2).

To sum up above three formulas, GHG emission ($E_m$) of manure storage in biogas and other alternative ways was calculated as below Equation (S2). The GHG equivalent for methane and $N_2O$ are 25 and 298 respectively (from IPCC, 2006).

$$E_m = CH_{4E} \times 25 + (N_2O_D + N_2O_G) \times 298 \quad \text{(S2)}$$

### *1.4. GHG Emission from Energy Usage*

Each type of fuel has different heating values and efficiencies of heat generation in their respective types of stove, leading to varying GHG emissions per MJ of useful heat. Effective heat delivered by different fuels are shown in Table S3 (NB: biogas stoves in Chinese rural households are the same as LPG and natural gas stoves, with a thermal conversion efficiency of 60% and heat value of 20,908 kJ·$m^{-3}$).

$$E_i = (f_{iCO2} \times 10^{-3} + f_{iCH4} \times 25 \times 10^{-3} + f_{iN2O} \times CVAE_i \times 10^{-9} \times 298) \times ES_i$$

where, $E_i$ is GHG emission during combustion for energy $i$, in kg $CO_2$-eq. $f_{iCO2}$ is $CO_2$ emission factor for energy i. $f_{iCH4}$ is $CH_4$ emission factor for energy $i$. $f_{iN2O}$ is $N_2O$ emission factor for energy $i$, $CVAE_i$ is average net calorific power of replaced energy $i$. $ES_i$ is the amount of energy $i$, and, specific emission factor listed in Table S4.

Fossil fuels such as coal and LPG give rise to GHG emissions during extraction and transportation, as well as during combustion (biofuels such as straw, firewood and biogas are usually collected locally by manpower, so emissions from extraction and transportation are negligible). GHG emissions from energy extraction and transportation were calculated using energy consumption activity data and respective emission factors taken from Zhang et al. [4] who adopted an LCA approach (Table S5).

$$IE_i = (E_{mi} + E_{ti}) \times ES_i$$

where, $IE_i$ is GHG emission during energy extraction and transportation for energy $i$, kg $CO_2$-eq; $E_{mi}$ is GHG emission for energy extraction for $i$. $E_{ti}$ is GHG emission for energy transportation for $i$, and, related emission factor listed in Table S5.

GHG emission mitigation from RHB can be calculated as Equation (S3).

$$E_t = E_i + IE_i - E_b \quad \text{(S3)}$$

where, $E_t$ is GHG mitigation from RHB. $E_i$ is GHG emission during combustion of traditional energy $i$. $IE_i$ is GHG emission during energy extraction and transportation for energy $i$, kg $CO_2$-eq. $E_b$ is GHG emission during combustion of biogas (Table S4).

### *1.5. GHG Mitigation from Nutrient Substitution*

Chemical fertilizer is a significant source of GHG emissions from its production and application [3]. Digestate is a nutrient-rich organic fertilizer which can substitute chemical fertilizers. We estimated the nutrient input and output for the biogas system using farmer survey data, and monitored the final usage of nutrients in digestate based on laboratory analysis of nutrient concentrations. If digestate was all used as a fertilizer, then the reduced chemical fertilizer substitution effect of RHB systems could be estimated. The nutrient input and output of biogas facility was calculated by below formula.

$$I_{(i)} = (M_{(i)} \times d_m + H_{(i)} \times d_h) \times 10^{-3}$$

where, $I_{(i)}$ is the nutrient input, in kg, and, *i* means N, $P_2O_5$ or $K_2O$. $M_{(i)}$ is *i* content in livestock manure, in g·kg$^{-1}$ (measured by this research, Table S6). $H_{(i)}$ is *i* content in human waste (i.e., feces and urine), in g·kg$^{-1}$ (measured by this research, Table S6). $d_m$ and $d_h$ refer to the amount of livestock manure and human waste put into digester, in kg (measured by this research, Table S7):

$$O_{(i)} = (L_{(i)} \times d_l + S_{(i)} \times d_s) \times 10^{-3}$$

where, $O_{(i)}$ is output of *i* from RHB, in kg. $L_{(i)}$ is *i* content in biogas slurry, in g·L$^{-1}$ (measured by this research, Table S6). $S_{(i)}$ is *i* content in biogas residue, in g·kg$^{-1}$ (measured by this research, Table S6). $d_l$ is amount of biogas slurry output from RHB, in L, and $d_s$ is amount of biogas residue output from RHB, in kg (Table S7).

Nutrient retention:

$$E_{(i)} = O_{(i)}/I_{(i)}$$

where, $E_{(i)}$ is nutrient retention efficiency, and the data are from sample measurements (Table S7).

$$E_r = E_{(i)} \times \left(M_{(i)} \times dm\right) \times f_g \quad \text{(S4)}$$

where, $E_r$ is the GHG emission of nutrient supplied by biogas residue, in kg $CO_2$-eq. $M_{(i)}$ is *i* content in livestock manure and human waste, in kg. $d_m$ is the amount of livestock manure and human waste put into digester, in kg. Emission factors ($f_g$) were directly cited from Zhang et al. [4] who adopted a LCA approach (Table S8).

### *1.6. GHG Emission from Biogas Leakage and Loss*

Biogas leakage from RHB systems was estimated as the gap between gas production and gas usage. We estimated biogas production by ABEPE model [4]. The concept of this model is to estimate energy production by biomass input and energy conversion coefficients for each type of biomass under different climate conditions.

For most fermentation in RHB systems in China without additional heating, the inner digester temperature should be close to the average temperature at 1.6 m underground [5], leading to a revised biogas production formula:

$$B_u = \sum_{i}^{n} (R_{(i)} \times P_i \times DM_{if} \times Fac_i) \times T_{In} \times L$$

where, $B_u$ is gas production, m$^3$·year$^{-1}$. $R_i$ is the biogas produced by *i material*, in kg. $P_i$ is the ratio of *i* added by all materials. $DM_{if}$ is the conversion factor of dry material of *i*, non-dimensional. $Fac_i$ is gas factor of *i* for dry material (at 35 °C), in m$^3$·kg$^{-1}$. $T_{In}$ is relative gas rate factor at T °C for 1.6 m underground, non-dimensional [6]. *L* is production time, in 0–1 year, the relevant parameter to Table S9.

$$E_l = (B_u - B_s) \times 1.221 \times 60\% \times 25 + (B_u - B_s) \times 1.221 \times 40\% \quad \text{(S5)}$$

where, $E_l$ is GHG emission for the gas loss, in kg·$CO_2$-eq. $B_s$ is gas consumed by household (recorded by our meter), in m$^3$. 1.221 is gas density at 25 °C and 101 kpa, in kg·m$^{-3}$. 60% is methane proportion of biogas (data from Zhou [7]). 25 is calescence potential for methane (IPCC2007). 40% is $CO_2$ proportion of biogas (data from Zhou [7]).

## 2. Supplementary Results

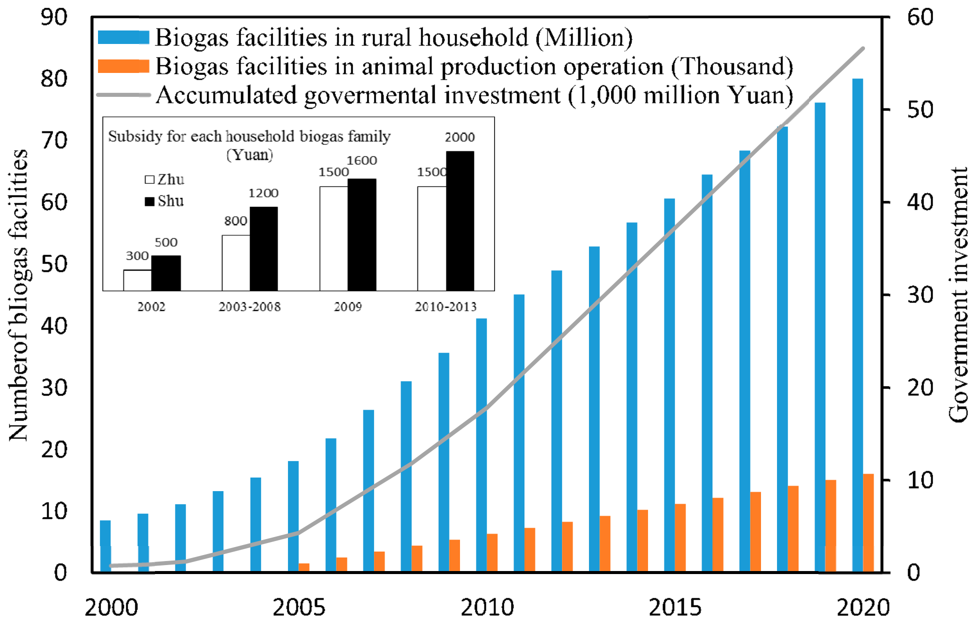


**Figure S1.** Increases in biogas digester units (cumulative) and government support provided as subsidies (cumulative). The latter is equivalent to nearly U.S. $9000 million by 2020. Source: the authors, and data is from reference [8–10].

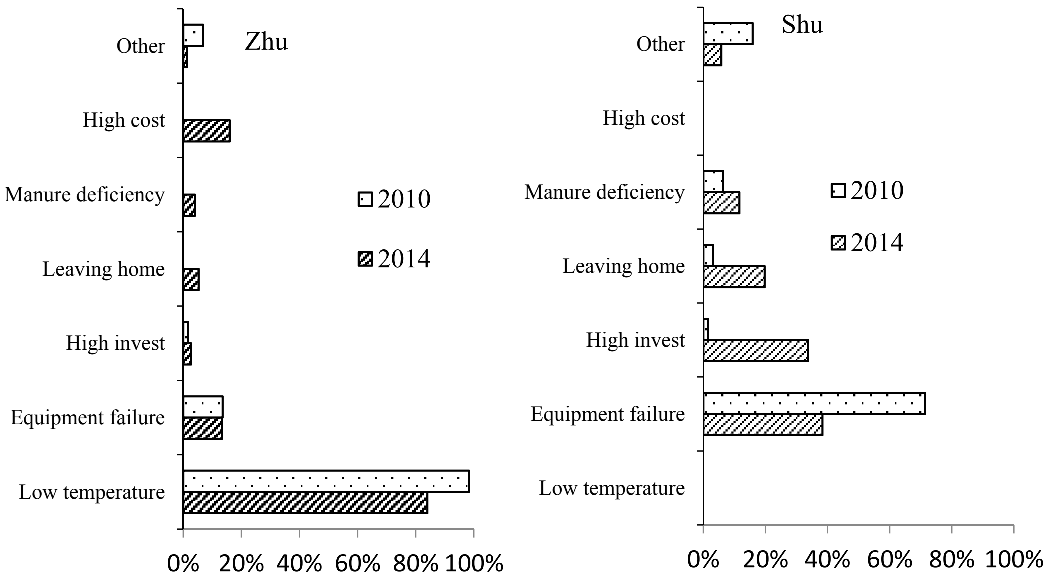


**Figure S2.** Reasons for abandoning RHB, including abandoning construction or an operation RHB. Percentage of reasons exceeded 100% because some farmers gave more than one reason for stopping a RHB.

**Table S1.** The numbers of biogas and non-biogas farms and main categories in the survey.

| Site | August–October 2010 | | August–October 2014 | |
|---|---|---|---|---|
| | **Biogas Farms (Interview Number/Total)** | **Non-Biogas Farms (Interview Number/Total)** | **Biogas Farms (Interview Number/Total)** | **Non-Biogas Farms (Interview Number/Total)** |

| | | | | |
|---|---|---|---|---|
| Zhu | 78/93 | 153/200 | 15/25 | 150/260 |
| Shu | 95/154 | 150/300 | 97/160 | 86/270 |

| Category | Questions |
|---|---|
| Household | Name, education of head of a household, occupation besides farmer, number of members, total land area |
| | land of livestock and field |
| Livestock production | Animal category , weights of animals, diets and feeding methods |
| Crop production | Crop category, fertilizer usage, yield |
| Residue management | Straw usage and amount |
| Manure management | Technology for manure collection, end use of manure (crop, biogas, discharge, sell) |
| Biogas | Ratio for installing RHB |
| | Construction cost and materials of RHB |
| | RMB support, how often were sediment removed and manure added, end use of biogas |
| Energy | Energy category, cost of all kinds of energy |

Note: Source: the authors.

**Table S2.** GHG emission factors for manure management.

| Village | Manure Treatment | MCF (%) | $EF_s$ (kg $N_2O$-N kg$^{-1}$ Excreted N) | $Frac_{GasMs}$ (%) | $EF_4$ (kg $N_2O$-N kg$^{-1}$ ($NH_3$-N + $NO_X$-N Emission)) |
|---|---|---|---|---|---|
| Zhu | Stack | 2 | 0.005 | 30 | 0.01 |
| Shu | Anaerobic lagoon | 77 | 0.002 | 25 | 0.01 |

Note: Source: IPCC2006. MCF indicates methane conversion factors; $EF_s$ is direct emission factor in manure management system; $Frac_{GasMs}$ is the ratio of $NH_3$ and $NO_X$ as emission form in manure management; $EF_4$ is emission factor of $N_2O$ in soil and N deposition.

**Table S3.** Calculation parameters of energy consumption.

| Energy Types | [a] Coefficient of Converting to CE (kg·ce·kg$^{-1}$) | [b] Thermal Conversion Efficiency (%) | [a] Heat Value (kJ·kg$^{-1}$) |
|---|---|---|---|
| LPG | 1.7143 | 55% | 50,179 |
| Coal | 0.714 | 35% | 20,908 |
| Firewood | 0.571 | 25% | 16,726 |
| Straw | 0.429 | 25% | 14,636 |
| Biogas | 0.714 | 60% | 20,908 kJ·m$^{-3}$ |
| Electricity | 0.1229 kWh$^{-1}$ | 80% | 3569 kJ·kWh$^{-1}$ |

Note: Source: the authors. [a] Data is from National Bureau of Statistics of China [11] and CE = coal equivalent. [b] Data is from Gnansounou et al. [12].

**Table S4.** GHG emission factor of energy consumption.

| Item | $CO_2$ (g·kg$^{-1}$) | $CH_4$ (g·kg$^{-1}$) | $N_2O$ (kg·TJ$^{-1}$) |
|---|---|---|---|
| Straw | 1130 | 4.56 | 4 |
| Firewood | 1450 | 2.7 | 4.83 |
| Coal | 2280 | 2.92 | 1.4 |
| Oil | 3130 | 0.0248 | 4.18 |
| Biogas | 748 | 0.023 | - |
| LPG | 3075 | 0.137 | 1.88 |
| Natural gas | 117,500 (kg·TJ$^{-1}$) | 1.24 (kg·TJ$^{-1}$) | 1.84 |
| Coal gas | 92,500 (kg·TJ$^{-1}$) | - | - |
| Electricity | 1.0577 (Mg·MWh$^{-1}$) | - | - |

Note: Source: the authors. Data is from Liu et al. [13].

**Table S5.** GHG emission factors of energy extraction and transportation.

| Energy Type | Per Energy Products [4] | GHG Emission of Transportation [4] |
|---|---|---|

| | | |
|---|---|---|
| Coal | 0.24 $Mg \cdot CO_2$-eq$\cdot Mg^{-1}$ | 0.019 $kg \cdot CO_2$-eq$\cdot kg^{-1}$ |
| Electricity | 1.12 $kg \cdot CO_2$-eq$\cdot kWh^{-1}$ | 0 |
| Natural gas | 0.07 $kg \cdot CO_2$-eq$\cdot m^{-3}$ | 0 |
| LPG | 0.27 $Mg \cdot CO_2$-eq$\cdot Mg^{-1}$ | 0.012 $kg \cdot CO_2$-eq$\cdot kg^{-1}$ |

Note: Source: the authors. Data is from Zhang et al. (2013) [3].

**Table S6.** Contents of nutrients in manures, digestate and wastes.

| | Unit | N | $P_2O_5$ | $K_2O$ | Source |
|---|---|---|---|---|---|
| Cattle manure (dry matter) | $g \cdot kg^{-1}$ | 21.70 ± 1.70 | 6.00 ± 0.00 | 7.35 ± 0.35 | This research |
| Digestate of cattle manure (dry matter) | $g \cdot kg^{-1}$ | 24.19 ± 4.19 | 7.63 ± 0.64 | 11.64 ± 1.64 | This research |
| Digestate of cattle manure (fresh matter) | $g \cdot L^{-1}$ | 1.96 ± .96 | 0.03 ± 0.03 | 1.44 ± 0.44 | This research |
| Pig manure (fresh matter) | $g \cdot kg^{-1}$ | 6.9 ± 0.9 | 9.00 ± 0.90 | 3.80 ± 0.80 | This research |
| Digestate of pig manure (dry matter) | $g \cdot kg^{-1}$ | 3.46 ± 0.46 | 7.30 ± 0.36 | 3.57 ± 0.57 | This research |
| Digestate of pig manure (fresh matter) | $g \cdot L^{-1}$ | 1.49 ± 0.49 | 0.18 ± 0.18 | 0.10 ± 0.18 | This research |
| Human faeces and urine | $g \cdot kg^{-1}$ | 6.40 | 1.10 | 1.90 | China organic nutrients [14] |
| | | | Dry matter content (%) | | Source |
| Cattle manure (fresh matter) | | | 24% ± 4% | | This research |
| Digestate of cattle manure (fresh matter) | | | 28% ± 8% | | This research |
| Pig manure (fresh matter) | | | 30% ± 2% | | This research |

Note: Source: the authors.

**Table S7.** Nutrient retention of biogas digesters in the two villages.

| Item | Zhu Village ($kg \cdot household^{-1}$) | | | Shu Village ($kg \cdot household^{-1}$) | | |
|---|---|---|---|---|---|---|
| | N | $P_2O_5$ | $K_2O$ | N | $P_2O_5$ | $K_2O$ |
| Input | | | | | | |
| Human waste | 10.53 ± 2.87 | 1.81 ± 0.49 | 3.13 ± 0.85 | 9.85 ± 1.94 | 1.69 ± 0.33 | 2.92 ± 0.57 |
| Manure | 23.14 ± 6.06 | 6.40 ± 1.68 | 7.84 ± 2.05 | 38.86 ± 17.09 | 48.08 ± 22.29 | 20.30 ± 9.41 |
| Total | 33.67 ± 6.79 | 8.21 ± 1.76 | 10.96 ± 2.25 | 46.71 ± 17.90 | 49.77 ± 22.42 | 23.22 ± 9.64 |
| Output | | | | | | |
| Liquid digestate | 9.49 ± 0.75 | 0.14 ± 0.01 | 6.96 ± 0.55 | 23.15 ± 6.25 | 17.09 ± 4.62 | 1.55 ± 0.42 |
| Solid digestate | 8.18 ± 0.65 | 2.58 ± 0.20 | 2.58 ± 0.20 | 10.38 ± 2.79 | 21.90 ± 5.88 | 16.92 ± 4.54 |
| Total | 17.65 ± 1.39 | 2.73 ± 0.22 | 9.54 ± 0.75 | 33.53 ± 6.58 | 38.99 ± 7.10 | 18.47 ± 4.52 |
| Conversion efficiency | 54% | 34% | 89% | 81% | 92% | 92% |

Note: Source: the authors.

**Table S8.** GHG emission during chemical fertilizer production and transportation.

| | Process | N ǂ | $P_2O_5$ * | $K_2O$ * |
|---|---|---|---|---|
| Emission factors (kg $CO_2 \cdot kg^{-1}$) | Fertilizer production | 8.2 | 0.73 | 0.50 |
| | Fertilizer transportation | 0.1 | 0.06 | 0.05 |
| | Total | 8.3 | 0.79 | 0.55 |

Note: Source: the authors. ǂ Data are from a study by Zhang et al. [3], and fertilizer production include energy mining, $NH_3$ synthesis and production. * Data are from a study by Chen et al. [15].

**Table S9.** The estimated biogas yields of households.

| Village | Source | $Fac_{cf}$ [a] ($m^3 \cdot kg^{-1} \cdot$ DM) | Digester Capacity ($m^3$) | Temperature of 1.6 m Underground (°C) | Speed Factor of 1.6 m $T_{In}$ | Source Amount (t) | Production Time (years) | Theoretical Biogas Yields ($m^3$) | Average Biogas Yields ($m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| Zhu | Dairy manure | 0.19 | 8 | 20 | 0.80 | 3.6–9.1 | 0.58 (Mar.–Sep.) | 40.2–136.0 | 82.5 |
| Shu | Pig manure | 0.42 | 8–30 | 25 | 0.89 | 2.0–17.8 | 0.83 (Mar.–Dec.) | 65.8–768.0 | 274.6 |

Note: Source: the authors. [a] Data is from Møller et al. [16].

**Table S10.** Cropland and livestock.

| Item | 2009/10 |
|---|---|

| | Zhu | | Shu | |
|---|---|---|---|---|
| | **Biogas** | **Non-Biogas** | **Biogas** | **Non-Biogas** |
| Cropland (ha) | 0.85 ± 0.51 | 0.73 ± 0.35 | 0.34 ± 0.17 | 0.27 ± 0.18 |
| Pig or cattle (capita) | 3.0 ± 1.9 | 3.6 ± 2.2 | 1.7 ± 2.0 | 1.6 ± 2.0 |
| Crop type | Wheat/maize-peanut | Wheat/maize-peanut | Wheat/maize (red tomato), rice | Wheat/maize (red tomato), rice |

Note: Source: the authors.

**Table S11.** Nutrient content of different crop straws.

| | **Unit** | **N** | **$P_2O_5$** | **$K_2O$** | **Source** | **Ratio of Crop Straw to Grain [17]** |
|---|---|---|---|---|---|---|
| Maize | % | 0.92 | 0.35 | 1.42 | China organic nutrient [14] | 1.75 |
| Sweet tomato | % | 2.37 | 0.65 | 3.66 | China organic nutrient [14] | 0.70 |
| Wheat | % | 0.31 | 0.09 | 0.78 | China organic nutrient [14] | 1.16 |
| Rice | % | 0.30 | 1.10 | 0.80 | China organic nutrient [14] | 0.90 |
| Peanut | % | 1.82 | 0.37 | 1.31 | China organic nutrient [14] | 1.94 |
| Direct return | % | 100 | 100 | 100 | Gao et al. [18] | |
| Burning | % | 0 | 70 | 70 | Gao et al. [18] | |

Note: Source: the authors.

**Table S12.** Manure treatment in Zhu and Shu in 2009/2010.

| **Site** | **Farmer** | **Manure (Mg)** | **Treatments of Manure** | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Biogas Digester (Mg)** | **Stack (Mg)** | **No Treatment (Sell) (Mg)** | **Anaerobic Lagoon (Mg)** | **Other (Mg)** |
| Zhu | Biogas | 69.3 ± 43.6 | 3.0 ± 0.8 | 30.1 ± 20.3 | 32.4 ± 36.3 | - | 3.8 ± 16.5 |
| | Non-biogas | 38.8 ± 37.4 | - | 18.8 ± 18.9 | 19.3 ± 26.7 | - | 0.8 ± 5.4 |
| Shu | Biogas | 5.6 ± 5.0 | 5.2 ± 4.1 | 0 | 0 | 0.4 ± 1.8 | 0 |
| | Non-biogas | 4.9 ± 5.5 | - | 0.1 ± 0.8 | 0.1 ± 0.8 | 4.7 ± 5.2 | 0.03 ± 0.2 |
| | **Type** | **Sample Number** | **The Number of Farmer's Manure Treatments** | | | | |
| | | | **RHB** | **Stack** | **No Treatment (Sell)** | **Anaerobic Lagoon** | **Discard** |
| Zhu | Biogas | 78 | 4 | 73 | 78 | - | 61 |
| | Non-biogas | 153 | - | 114 | 153 | - | 112 |
| Shu | Biogas | 95 | 91 | 0 | 0 | | 0 |
| | Non-biogas | 87 | - | 0 | 1 | | 3 |

Note: Source: the authors. n: number of households. Manure management method: No treatment means fresh manure. Stack is the solid fraction from separation of manure that have been stored in heaps for random time without turning and additive, similar but different to compost. RHB means that has been in biogas digester.

**Table S13.** Household income and average years of education completed by the head of the household.

| **Site** | **Treatment** | **Annual Income (Yuan, RMB)** | **Agricultural Income (Yuan, RMB)** | **Ratio (%)** | **Education (years)** |
|---|---|---|---|---|---|
| Zhu | Biogas | 23,612 ± 21,109 | 14,817 ± 15,014 * | 63 | 7.9 ± 2.9 |
| | Non-biogas | 16,062 ± 14,826 | 9328 ± 7395 | 58 | 6.9 ± 3.1 |
| Shu | Biogas | 24,556 ± 19,750 | 2396 ± 3218 | 10 | 6.9 ± 3.0 |
| | Non-biogas | 24,003 ± 25,189 | 1793 ± 3162 | 7 | 4.9 ± 3.1 |

Note: Source: the authors. * means $p < 0.05$ between biogas and non-biogas farmers with independent samples *t* test.

**Table S14.** Energy consumption by source in biogas and non-biogas households in the two villages in 2009/10.

| **Energy Type** | **Unit** | **Primary Energy Consumption** | | **Primary Energy Effective Thermal** | |
|---|---|---|---|---|---|
| | | **Zhu** | **Shu** | **Zhu** | **Shu** |

| | | **Biogas (*n* = 71)** | **Non-Biogas (*n* = 153)** | **Biogas (*n* = 71)** | **Non-Biogas (*n* = 153)** | **Energy Type** | **Biogas (*n* = 95)** | **Non-Biogas (*n* = 150)** | **Biogas (*n* = 95)** | **Non-Biogas (*n* = 150)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Electricity | kWh | 995 ± 470 | 816 ± 382 | 795 ± 389 | 611 ± 396 | Electricity | 20 ± 9 | 16 ± 8 | 27 ± 13 | 21 ± 14 |
| LPG | kg | 30 ± 5 | 31 ± 19 | - | - | LPG | 28 ± 9 | 29 ± 18 | - | - |
| Straw | kg | - | - | 758 ± 703 | 933 ± 440 | Straw | - | - | 96 ± 91 | 120 ± 57 |
| Firewood | kg | - | - | 341 ± 321 | 544 ± 291 | Firewood | - | - | 49 ± 46 ** | 78 ± 42 |
| Coal | kg | 2113 ± 682 | 2059 ± 720 | - | - | Coal | 149 ± 91 | 150 ± 94 | - | - |
| Biogas * | $m^3$ | 47 ± 21 | - | 173 ± 73 | - | Biogas * | 12 ± 5 | - | 45 ± 19 | - |
| Total | | | | | | Total | 209 | 195 | 217 | 219 |

Note: Source: the authors.

**Table S15.** Estimated energy consumption of all households including biogas and non-biogas farmers in 2009/10.

| **Energy Use** | **Electricity** | **Petrol Gas** | **Coal** | **Straw** | **Firewood** | **Biogas** |
|---|---|---|---|---|---|---|
| | | Distribution of energy types in Zhu (%) | | | | |
| Cooking | 20 | 100 | 30 | - | - | 100 |
| Illumination | 25 | 0 | 0 | - | - | 0 |
| Heating | 10 | 0 | 70 | - | - | 0 |
| Others | 45 | 0 | 0 | - | - | 0 |
| | | Distribution of energy types in Shu (%) | | | | |
| Cooking | 35 | - | - | 100 | 100 | 100 |
| Illumination | 15 | - | - | 0 | 0 | 0 |
| Heating | 15 | - | - | 0 | 0 | 0 |
| Others | 35 | - | - | 0 | 0 | 0 |

Note: Source: the authors.

**Table S16.** Fertilization of biogas and non-biogas household in two villages in 2009/10.

| **Village** | **Farmer** | **Term** | **Biogas Residue ($Mg·DM·ha^{-1}$)** | **Manure ($Mg·DM·ha^{-1}$)** | **Chemical Fertilizer ($kg·ha^{-1}$)** | | | **Yield ($Mg·ha^{-1}$)** |
|---|---|---|---|---|---|---|---|---|
| | | | | | **N** | **$P_2O_5$** | **$K_2O$** | |
| Zhu | Biogas family | Maize | 0 | 29.8 ± 11.1 | 296.0 ± 92.9 | 100.8 ± 38.3 | 109.2 ± 29.6 | 8.1 ± 1.3 |
| | | Wheat | 0 | 28.8 ± 10.7 | 294.3 ± 87.7 | 112.4 ± 100.7 | 107.1 ± 30.4 | 4.4 ± 1.3 |
| | | Peanut | 0 | 25.7 ± 9.2 | 134.9 ± 77.0 | 89.6 ± 25.1 | 89.3 ± 23.8 | 3.3 ± 0.5 |
| | Non-biogas family | Maize | 0 | 28.6 ± 10.4 | 316.0 ± 94.3 | 92.2 ± 24.4 | 100.1 ± 29.4 | 7.8 ± 4.2 |
| | | Wheat | 0 | 28.9 ± 9.9 | 329.6 ± 90.6 | 90.5 ± 22.9 | 95.2 ± 26.9 | 5.1 ± 4.4 |
| | | Peanut | 0 | 26.1 ± 10.0 | 113.5 ± 60.8 | 88.1 ± 21.8 | 88.7 ± 21.1 | 3.3 ± 1.9 |
| Shu | Biogas family | Maize | 16.6 ± 7.6 | 0 | 300.0 ± 180.0 | 104.7 ± 83.8 | 4.7 ± 21.1 | 4.5 ± 1.1 |
| | | Wheat | 16.5 ± 7.7 | 0 | 79.9 ± 76.0 | 49.2 ± 40.3 | 4.0 ± 18.9 | 3.5 ± 0.7 |
| | | Rice | 15.6 ± 10.0 | 0 | 118.9 ± 87.4 | 52.7 ± 43.0 | 3.5 ± 16.4 | 5.8 ± 0.7 |
| | Non-biogas family | Maize | 0 | 18.0 ± 7.4 | 302.8 ± 147.4 | 95.9 ± 62.3 | 3.2 ± 0.0 | 3.7 ± 0.8 |
| | | Wheat | 0 | 16.1 ± 7.9 | 74.5 ± 34.5 | 40.0 ± 18.0 | 0.8 ± 0.0 | 3.2 ± 0.3 |
| | | Rice | 0 | 8.9 ± 6.0 | 130.9 ± 48.8 | 47.0 ± 25.5 | 1.7 ± 0.0 | 5.5 ± 0.6 |

Note: Source: the authors.

**Table S17.** Straw use in different ways of the two groups of farmers in 2009/10.

| **Straw Management** | **Zhu (kg, DM)** | | **Shu (kg, DM)** | |
|---|---|---|---|---|
| | **Biogas (*n* = 78)** | **Non-Biogas (*n* = 153)** | **Biogas (*n* = 95)** | **Non-Biogas (*n* = 150)** |
| Feed | 9029 ± 7547 | 7968 ± 5722 | 797 ± 622 | 702 ± 1302 |
| Energy | 179 ± 745 | 206 ± 897 | 1268 ± 1109 | 1351 ± 1076 |
| Direct use | 68 ± 545 | 0 ± 0 | 679 ± 1271 | 310 ± 510 |
| Discard | 111 ± 520 | 25 ± 210 | 42 ± 187 | 36 ± 156 |
| Burning in field | 0 ± 0 | 13 ± 120 | 1 ± 11 | 25 ± 259 |
| Burning beside field | 0 ± 0 | 81 ± 411 | 415 ± 2646 | 0 ± 0 |
| Sell | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |

Note: Source: the authors.

**Table S18.** Straw nutrient content and use in 2009/10.

| | N ($kg·household^{-1}$) | | | | $P_2O_5$ ($kg·household^{-1}$) | | | | $K_2O$ ($kg·household^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2009/10** | **Zhu** | | **Shu** | | **Zhu** | | **Shu** | | **Zhu** | | **Shu** | |
| | Biogas | Non-biogas | Biogas | Non-biogas | Biogas | Non-biogas | Biogas | Non-biogas | Biogas | Non-biogas | Biogas | Non-biogas |
| Feed | 104 ± 105 | 86 ± 60 | 19 ± 15 | 17 ± 31 | 32 ± 27 | 27 ± 20 | 5 ± 4 | 5 ± 8 | 124 ± 103 | 106 ± 80 | 29 ± 23 | 26 ± 48 |
| Energy | 3 ± 13 | 3 ± 11 | 10 ± 9 | 11 ± 12 | 1 ± 3 | 1 ± 3 | 4 ± 4 | 5 ± 4 | 2 ± 10 | 4 ± 13 | 17 ± 15 | 19 ± 19 |
| Direct use | 3 ± 10 | 1 ± 3 | 6 ± 16 | 3 ± 7 | 1 ± 2 | 0 ± 1 | 5 ± 7 | 3 ± 4 | 5 ± 9 | 3 ± 6 | 11 ± 26 | 5 ± 12 |
| Discard | 3 ± 9 | 1 ± 4 | 0 ± 1 | 0 ± 2 | 1 ± 2 | 0 ± 1 | 0 ± 2 | 0 ± 1 | 4 ± 10 | 3 ± 6 | 0 ± 2 | 1 ± 3 |
| Burning in field | 1 ± 3 | 1 ± 6 | 0 ± 0 | 0 ± 2 | 0 ± 1 | 0 ± 2 | 0 ± 0 | 0 ± 1 | 3 ± 8 | 2 ± 14 | 0 ± 0 | 0 ± 4 |
| Burning beside field | 4 ± 22 | 3 ± 8 | 4 ± 24 | 0 ± 0 | 1 ± 6 | 1 ± 2 | 1 ± 9 | 0 ± 0 | 10 ± 55 | 5 ± 8 | 6 ± 37 | 0 ± 0 |
| Total | 117 ± 110 | 96 ± 60 | 39 ± 36 | 31 ± 37 | 35 ± 29 | 30 ± 20 | 16 ± 14 | 12 ± 12 | 148 ± 24 | 123 ± 83 | 62 ± 57 | 50 ± 58 |

Note: Source: the authors.

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