Get in Sanitation 2.0 by Opportunity of Rural China: Scheme, Simulating Application and Life Cycle Assessment

Bin Fan^{*}, Ming Hu, Hongliang Wang, Mingjie Xu, Bo Qu, Shikun Zhu

State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China; Laboratory of Water Pollution Control, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China.

Correspondence: Dr. Bin Fan
Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China;
Tel: +86-10-62849142;
Fax: +86-10-62849142;
E-mail: fanbin@rcees.ac.cn

Abstract

This study advances a scheme of sanitation 2 system (S2S) basing on vacuum source-separation to manage the rural waste and wastewater of Changshu, China. The advanced San-2 technology system parts the whole regional rural waste and wastewater into three parallel logistic streams, biogenic waste, other waste, and light grey water. A simulating application of S2S in a township area of Changshu is studied and evaluated by using the life cycle assessment method within the proposed framework and assumptions. Both the systems are divided into four parts: collection, treatment, termination and added processes. And the results show that San-2 has extraordinary advantages of environmental performance over conventional sanitation system (CSS), and the damage scores of the former are 27%, 54%, 27% and 37% as those of the latter with regarding the impacts on human health, ecosystem quality, climate change, and resources respectively. The environmental impact of the CSS is mainly sourced from the added processes, while that of the S2S is mainly from collection and treatment process. Sensitivity analysis shows that the ammonia emission rate and canceling biogas production are the key factor for the S2S, and the settlement population is the critical factor for the CSS. Facing the huge demands of the rural China, the S2S and the rural China are an opportunity to each other, and it is urged to setup encouraging policies for S2S to break up the dictatorship of the CSS.

Key words: sanitation 2.0; conventional sanitation; rural waste; vacuum source-separation; Changshu

1. Introduction

Sanitation refers to remove and treat the wastes-generated by human settlements to create hygienic conditions and prevent disease (Flores, 2010). Fast-forward 100 years, the conventional sanitation (Con-San) symbolizes with water-flush toilet, mixed-wastewater collection and energy-intensive wastewater treatment technology (Hu et al., 2016). However, Con-San always views wastewater as “waste” that requires complex technology and expertise to dispose, which consuming enormous amounts of energy and resources. In fact, the “waste” contains many valuable resources, namely nutrients, organic matter and water. There is therefore a need to investigate alternative sanitation options that may reuse or recycle the “waste”. Scientists and engineers have been exploring ways to develop a revolutionary sanitation that is more sustainable, affordable and resources reclaimable (Gretchen, 2012; Sunita, 2012; van Loosdrecht et al., 2014). The representative works include the ecological sanitation (Andersson et al., 2013), the sustainable sanitation (Gretchen, 2012), and the resource-oriented sanitation (Grant et al., 2012). Considering the characteristics and development of conventional sanitation, these revolutionary sanitations could be called Sanitation 2.0 (San-2).

Sanitation 2.0 is expected to sanitize urine and feces, recover nutrients for food production, and prevent environmental pollutions while minimizing the demand on other resources (Zhou et al., 2010). With the efforts and cooperations of scientists, engineers and social activists, the San-2 has obtained so abundant achievements in R&Ds and worldwide demonstrative applications (Greg, 2012; Langergraber et al., 2005; Zhou et al., 2010). However, the dictatorship of Con-San in real application market is as firm as before. The current application and development of San-2 is mainly aim to deal with the basic hygiene issue of the most poor countries which resulting the cheap but inferior user experience (Larsen et al., 2009), or substitute for the existing Con-San system by changing residents’ habits which annoying many users. Therefore, there are increasing needs for developing a suitable San-2.

Vacuum source-separation technology is a potential alternative to solve the issues. Vacuum toilet, one of key user interface, is similar with the conventional water-flush toilet in appearance, usage and comfort, but differs in the volume and characteristics of the black water (urine, faeces and flushing water) (Oarga Mulec et al., 2016). Vacuum toilets use 0.5-1.0 L of flushing water on average and produce 5-7 L of black water per person per day, which contains high concentrations of nutrients, such as 1.4-1.7 g/L of N and 0.15-0.2 g/L of P (Todt, 2015). However, conventional toilets produce about 10 times more wastewater, with one in 25 of concentrations of nutrients (Jenssen et al., 2004). Therefore, the black water with

small volumes and high concentration provides the greatest opportunities for reusing these “wastes”. Vacuum kitchen refuse processor, a conceptual household appliance, can crush the kitchen refuse into small pieces, and then collect these wastes by the vacuum sewer with a little sprinkling water (for washing and facilitating grinding). The product solves the problem of dumping the refuse, and can make use of these organic wastes. Vacuum source-separation realizes the source separation of main pollution loads by suitable user interface and collection methods (Thibodeau et al., 2014a), but without the technology of waste reuse.

Paulo et al. (2013) developed an evapotranspiration tank (TEvap) to treat the black water during a 400 days trial in a 9-person household in Campo Grande-MS, Brazil; Spangberg et al. (2014) employed storage as a low-tech hygiene treatment of black water by adding pH-increasing additives to reduce the storage time; Vogl et al. (2016) proposed the microbial fuel cells to treat the human black water in batch and continuous over 80 and 67 days; Oarga Mulec et al. (2016) presented an example of black water composting from vacuum toilet after the pretreatment of dewatering and mixing with pine bark and wheat bran. The above studies only individually deal with the black water but not the mixture of black water and kitchen refuse. Wendland (2008) systematically researched and assessed the anaerobic treatment of black water from vacuum toilets with and without kitchen refuse and its potential for resources recover sanitation concepts; Thibodeau et al. (2014a, 2014b) developed a black water source-separation sanitation system by employing anaerobic digestion to treat the black water and kitchen refuse. Therefore, anaerobic treatment is a viable option as a part of the separation system.

China is deliberating to launch a national-wide movement for the rural wastewater treatment. There is currently about 700 million rural residents, of which 90% percent haven't got sewage systems complying with environmental requests, and about a quarter even without toilets in accordance with modern standards (Hu et al., 2016). The upcoming huge demands provide opportunities to develop San-2 in rural China; especially, the modern sanitation needs have become intensive and elementally affordable along with the recent rapid progress in socio-economy and serious deterioration in eco-environment.

Therefore, the main objective of this study is to analyze the questions, demands and challenges of the Chinese rural sanitation system, and then advance a system scheme and strategy of San-2 basing on the recent technology progresses. A region-scale simulating application of San-2 is studied and evaluated by using the life cycle assessment.

2. Rural sanitation in China

2.1. Status qua and demands

Along with the development of the whole country, the Chinese rural society and economy has obtained big improvement in last 3 decades (Gao et al., 2016). The government has kept on attaching great importance to the rural water supply and hygiene, which are shown in Figure 1 (National Health and Family Planning Commission of the People's Republic of China, 2013). The rural household is subsidized to install six types of toilets, including two types of water-flush toilet (septic tank toilet and sewer-connected toilet), and four types of waterless toilet (dual-urn funnel toilet, biogas toilet, urine diverting dehydration toilet and alternating dual-pit toilet) (Hu et al., 2016). Additionally, the 'other toilets' in Figure 1 are elementally certain primitive waterless toilets of the local context too. According to Figure 1, there were 260 million rural households in 2012, of which 71.7% had installed certain toilets, including 32.8% of water-flush toilet and 38.9% of waterless toilet. However, only 8.8% of the Chinese rural households had got the sewer-connected toilets, and the other 91.2% or 240 million rural households hadn't got modern sanitation service.

Fig. 1. The recent progresses of the rural water supply and sanitation in China.

Sanitation system basing on waterless toilet has been intensively studied and widely applied in worldwide demonstrative projects (GIZ, 2012). Although waterless toilet is an appropriate choice when local economy and water-supply conditions don't permit to install water-flush toilet, it is not a prospective solution of San-2 when facing the requirements of modern life civilization. Table 1 analyzes the increments of the different toilets in Chinese rural areas from 2007 to 2012. Table S1 (see in Supplementary Information) presents the geographical sub-regions data in order to show the North-South differences in life style as well as geographical environment. The big increment of the biogas toilet (Figure 1) results from the promotion of the governments (Hou et al., 2012). If the biogas toilet being excluded, waterless toilet only contributed 6.12% to the total number increment and increased 3.67% in the recent five years while water-flush toilet contributed 70.64% and increased 53.12%. Comparing with waterless toilet, water-flush toilet is more often welcomed into everyday use. That is why the new sanitation system basing on waterless toilet has not yet evolved into an alternative of Con-San, such as the Erdos Eco-town Project (Flores, 2010; Winbald and Simpson-Hébert, 2004).

Table 1 Increment of the Chinese rural toilets from 2007 to 2012.

	Total	Water-flush	Waterless	Biogas	Waterless-biogas
Number (10 ⁶ hou)	41.86	29.57	12.29	9.73	2.56
Rate (%)	28.98	53.12	13.85	51.05	3.67

2.2. Pressing challenges from Con-San: the Practice of Changshu

The rapid urbanization of rural areas in China compels the government to take some actions to provide modern environment sanitation service for rural people (Tong et al., 2016). Although, the recent investment of conventional rural wastewater and waste treatment have arrived at hundreds of billion RMB (Statistical Bulletin of Urban-Rural Development, 2015), the qualified rate of the system construction and operation of the rural decentralized wastewater treatment are currently less than 40% and 20%, respectively. The 'Practice of Changshu' (see in Supplementary Information Text), mainly regarding with the conventional rural wastewater treatment, have been developed to deal with the issue of wastewater originating from the rural areas of China. The 'Changshu Practice' stands for the current trends of the rural sanitation system of China, and it is spreading over the country duo to the recommendation of central government. Although it may effectively help China to develop modern rural sanitation system, it do nothing help to prevent the inherent unsustainability of Con-San in economy and eco-environment. This situation is seriously worrying.

3. Materials

3.1. Testing application of vacuum source-separation in Changshu

Vacuum source-separation is one of resources-oriented technologies having been thoroughly studied (Remy, 2010; Todt, 2015; Zhang et al., 2014). It uses vacuum system to separately collect and transport toilet wastes (slurry). Vacuum toilet is widely employed in airplanes, ships and trains, and vacuum sewer is also a regular municipal wastewater collection technology especially being adopted where gravity sewer is inapplicable (Zeeman et al., 2007). A testing system of rural sanitation system basing on vacuum source-separation was built at Hehuageng Settlement, Guli Town of Changshu in 2011 (Hu et al., 2016). This is the first practical rural sanitation system using vacuum source-separation in China. Now the system has run properly for 5 years and gained highly recognition although it was ever deeply doubted by the local officials and residents at the beginning. *SI Text* (Supplementary Information Text) presents the details of the testing system. The testing system elementally proves techno-economic feasibility and advantages of the vacuum source-separation sanitation over Con-San. Vacuum source-separation has also been proved by many other engineering cases (Flores, 2010; GIZ, 2012; Zeeman et al., 2007). Comparing with the other new sanitation systems basing on waterless toilet, the most outstanding merit of vacuum source-separation lies in that it uses minimal water to immediately transfer the wastes from living places. Therefore, the vacuum-source separation is currently presented the best available technology for establishing San-2.

3.2. System scheme and strategies of San-2

China has a relatively dense rural population especially in flat areas, where a rural settlement is mostly with 50-500 households (200-2000 capita and 4 capita/hou) and a residential density of 50-100 capita/hm². The distance between settlements often ranges 0.5~5.0 km, which usually correlates negatively with settlement population. Such layout is beneficial to establish region-scale facility and management systems of San-2 as shown in Figure 2. The scheme is simply described in followings, and the detail is introduced in *SI Text*.

Grey water: to drain together with rainwater, or to be treated or reclaimed

Other wastes: to be sorted and collected, and then treated or disposed

Fig.2. The system scheme of San-2.

All the regional domestic wastes and wastewater are parted into three logistic streams: biogenic wastes (human excreta and food residues), other wastes (all the domestic solid wastes without solid food residues), and light grey water. Edible oil is excluded in the management of the other wastes stream, and it need be collected, treated and reused separately. And the in-settlement (inside settlement) system, including home sanitation and outdoor collection, should be planed and built according to the specific settlement conditions. The home sanitation and outdoor collection of biogenic wastes has two options, one is the high-level sanitation style (basing on vacuum source-separation technology), and another is the low-level sanitation style (employing waterless toilet). The low-level sanitation is a transitional solution for those settlements yet unsuitable to install vacuum source-separation system. And then a region ex-settlement (outside settlement) system should be planned and constructed to deal with these wastes according to the specific regional property. The ex-settlement system usually includes two parallel division systems, one is of the biogenic wastes, and another is of the other wastes. Lastly and very important, a sound management system should be organized for supporting technology system running.

Although the testing system of Hehuageng Settlement has partly proved the techno-economic feasibility of the San-2 system, it still need enough strong support especially of public power to break though the various barriers which began to be set and reinforced by Con-San since

the moment when water-flush toilet was invented. A more complete application of the San-2 system is simulated and compared with Con-San by life cycle assessment in the next section.

4. Methods

4.1. Case application region

Guli Town, one of the nine administrative townships of the Changshu City, will retain 200 rural settlements in its 92.06-km² areas, totally with 8959 households and 35, 000 inhabitants in the following 10 years. This township (including Hehuageng Settlement) is chosen as the simulating application region of San-2. For simplifying the case study, a model settlement is set to have 200 residents of 50 households with the population density of 80 capita/hm². Such assumptions elementally represent the local situations.

4.2. System models and assessment boundary

San-2 and Con-San employs the same way to collect and treat the other wastes, so the other wastes logistic stream is unnecessarily included in the comparative assessment. For the model settlement, a San-2 system (S2S) and a Con-San system (CSS) are equivalently planned as shown in Figure 3. Facility and operation features of the both systems are summarized in Table S2 and Table S3 (see in *SI Text*). For facilitating comparative assessment, both the sanitation systems are divided into four sections: collection, treatment, termination, and added process. The collection section covers the all facilities and processes before treatment. The treatment section covers the facilities and process of treatment and reclamation. The termination section covers the all process after treatment plant, including discharging and reuse. The facility and process of fertilization is not considered in this study because of limited data, but the environmental emissions related with fertilization are included in the assessment. Such dealing will not badly deteriorate fairness of the comparative assessment though the S2S will produce more organic fertilizer than the CSS. The added process, which is set wholly in the CSS, aims to trade off the reclaimed resources and energy between the S2S and the CSS. The extra outputs of the S2S are made equivalent respectively with the consumptions of chemical fertilizers and grid power in the added process (ISO I 14040, 2006; ISO I 14044, 2006). *SI text* presents the details of system models of the S2S and CSS.

Fig. 3. Models of the S2S and the CSS and the assessment boundary (the dotted lines).

Because of several-decade dependence on chemical fertilize application, the farmlands in China become severely mineralized, resulting extremely low plant efficiency of chemical fertilizers and deterioration of food quality. Duan et al. (2010) made an 18-year consecutive observation on the nitrogen recovery efficiency (NRE) of maize yield in an upland red soil farmland, with the different fertilization measures respectively as only chemical fertilizer, combined fertilizer (30% of chemical fertilizer and 70% of manure fertilizer), and only manure fertilizer. They reported that the current NREs of the three fertilization measures were 24.7%, 42.6% and 30.8%, respectively. Assuming the combined fertilization measure with 30% of chemical fertilizer and 70% of manure fertilizer is adopted in the S2S while the fertilizer measure with only chemical fertilizer is adopted in the CSS. To obtain the same quantity of crop-N, the equivalence relation between organic and chemical fertilizer is defined as shown below:

$$1 \text{ kg organic N} = \frac{42.6\%/24.7\% - 30\%}{70\%} \text{ kg chemical N} = 2.035 \text{ kg chemical N}$$

As for the P and K recovery efficiencies, no differences were observed between organic and chemical fertilizer (Gao et al., 2009; Wang et al., 2001; Zhu and Jin, 2013). Therefore in this study, 1 kg P/K of the reclaimed organic fertilizer is still equivalent to 1kg P/K of chemical fertilizer, respectively.

4.3. Life cycle assessment and the inventory

Environmental performance of the sanitation system is studied by using the LCA, as defined by ISO 14040 and 14044 (ISO I 14040, 2006; ISO I 14044, 2006). The scope of the assessment covers all foreground and background processes involving in the both systems, but end dismantling of the systems is not included because of limited data and low resources and energy consumptions (Emmerson et al., 1995). The functional unit is the collection, treatment, and by-product (biogas and organic fertilizers from anaerobic digestion) utilization of rural waste (wastewater and kitchen refuse) for one household for one year. Table S3 shows the mass flow and composition of reference flows. Life cycle inventory includes the input data that is used to model the relevant system components of studied systems, and output data that is the emission originating from the relevant processes of studied systems. General, system construction, system operation and background processes make up the inventory. Data for system construction is generated by a simplified layout of settlement in combination with secondary data from testing system. Data for system operation is described with explicitly stating process layout, underlying assumptions, data origin, and parameter

adjustment.

Considering the difference between China and Europe in the degree of industrialization and environmental restrictions, the Chinese Life Cycle Database (CLCD) v 0.8 (IKE, 2013), which is available in the software eBalance v 4.0 (IKE, 2015), is also adopted. Raw material and industrial energy consumption data are primarily from Chinese industry statistics (National Bureau of Statistics, 2013b), China energy statistics yearbook (National Bureau of Statistics, 2013a) and literatures. The water usage and main emission data are from the China Pollution Source Census (Ministry of Environmental Protection, 2014), and some emission data are derived from chemical equilibrium calculations (China National Petroleum & Chemical Network, 2013). Some processes data are from industry, modified as an estimation of industrial average rather than factory-specific data. According to the implemented projects of Changshu, the transportation distances for carrying the basic materials on site are estimated as 100 km for concrete and sand, 300 km for plastic, 500 km for steel and 600 km for chemicals. In general, nutrient emissions during application of the various types of fertilizer heavily depend on the application methods, weather conditions, soil type and condition (Remy, 2010). Consequently, nutrient emission rates in the literature are often given in ranges depending on boundary conditions. The nutrient emissions from the air tight reactors are considered negligible (Bluteau et al., 2009). Nutrient emission rates of the organic fertilizer and chemical fertilizer after farmland application are shown in Table 2. The results are introduced as damage scores corresponding to each indicator. The lower score, the better environmental performance is. All the damage scores are expressed in terms of per household per year. The IMPACT 2002+ (midpoint) and ReCiPe (midpoint) (Niero et al., 2014) methods are also used to evaluate the robustness of the results related with assessment software. *SI Text* proposes the details of LCA.

Table 2. Nutrient emission rates of the organic and chemical fertilizers after farmland application

Input	Output	Emit into	Emissions rates (kg/kg input)			
			Organic	References	Chemical ^a	References
N	NH ₃ -N	Air	0.2	(Yan et al., 2003)	0.116	(Ju et al., 2009)
N	N ₂ O-N	Air	0.005	(Zhou et al., 2010)	0.0104	(Yan et al., 2003)
N	NO _x -N	Air	0.002	(Thibodeau et al., 2014a)	0.0034	(Liu et al., 2013)
N ^b	NO ₃ ⁻ -N	Soil	0.0001	(Ti, 2011)	0.003	(Ju et al., 2009)
N ^c	NH ₄ ⁺ -N	River	0.021	(Zhao, 2009)	0.05	(Zhu, 2008)
P ^d	P	River	0.025	(Zhao, 2009)	0.0146	(Li, 2008)

^aN-fertilizers mix used in China is estimated of 66.1% urea and 33.9% other N fertilizers (using the ammonium nitrate as alternative).

^bLeaching Nitrogen in the form of nitrate.

^cRunoff Nitrogen in the form of ammonium.

^dRunoff Phosphorus emissions originating from runoff.

Table 3 Summary of the life cycle inventory of the CSS and the S2S.

Unit	Plastic kg/hou·y		Concrete m ³ /hou·y		Stainless steel kg/hou·y		Electricity kWh/hou·y		Transport ton·km/hou·y	
Stage/process	CSS	S2S	CSS	S2S	CSS	S2S	CSS	S2S	CSS	S2S
Collection	5.18E+00	1.84E+00	/	/	2.40E-01	0.51E+00	9.64E+01	7.22E+01	1.18E+01	7.96E+00
Vacuum sewer system and pump	/	1.28E+00	/	/	/	0.36E+00	/	6.02E+01	/	1.10E+00
Gravity sewer system and pump	4.47E+00	5.55E-01	/	/	2.40E-01	/	9.64E+01	/	8.44E-01	2.46E-01
Kitchen refuse collector	/	/	/	/	/	0.15E+00	/	1.20E+01	/	2.33E-01
Dust basket and Outdoor Dustbin	7.07E-01	/	/	/	/	/	/	/	1.73E+00	/
Waste transport	/	/	/	/	/	/	/	/	9.26E+00	6.38E+00
Treatment	/	3.27E+00	5.08E-02	1.08E-02	6.50E-01	3.21E-01	9.86E+01	5.56E+01	2.83E+01	8.02E+00
Wastewater treatment plant	/	/	4.63E-02	/	6.50E-01	/	9.72E+01	/	1.14E+01	/
Constructed wetland	/	/	/	4.80E-03	/	1.32E-03	/	/	/	1.64E+00
Anaerobic digestion	/	/	/	6.02E-03	/	3.20E-01	/	5.56E+01	/	1.66E+00
Sludge disposal plant	/	/	4.45E-03	/	/	/	1.40E+00	/	1.60E+01	/
Biogas scrubbing	/	/	/	/	/	/	/	/	/	3.11E+00
Biogas storage	/	3.27 E+00	/	/	/	/	/	/	/	1.64E+00
Incineration	/	/	/	/	/	/	/	/	9.49E-01	/
Added processes	/	/	/	/	/	/	1.46E+02	/	/	/
Total	5.18E+00	5.11E+00	5.08E-02	1.08E-02	8.90E-01	8.31E-01	3.41E+02	1.28E+02	4.01E+01	1.60E+01

5. Results and discussion

5.1 Environmental impact analysis

The detailed solutions of life cycle impact assessment are summarized in Table S5 and Table S6. The total and itemized damage scores of the both systems are obtained basing on the life cycle inventory (Table 3). The results show the S2S performs better than the CSS with regarding every indicator. Figure 4 shows the relative damage scores of the both systems by setting each total indicator score of the CSS as 100%. For the indicators of human health, ecosystem quality, climate change and resources, the damage scores of the S2S are respectively 27%, 54%, 27% and 37% as those of the CSS. This means the S2S has remarkable advantages of environmental performance over the CSS.

Fig. 4. Comparative impact scores and their compositions of the S2S and the CSS.

Source compositions of each total indicator scores of the both systems are also showed in Figure 4. The added process contributes 61%, 93%, 60% and 69% respectively to the impacts of the CSS on human health, ecosystem quality, climate change and resources. This implies the advantages of the S2S mainly come from its resources reclamation property. The S2S performs less advantage over the CSS in ecosystem quality than in the other three indicators. The termination sector of the S2S contributes 95% to the its total damage score of ecosystem quality, indicating that to decrease the emissions of the organic fertilizer application is significant for improving the S2S' performance with regarding ecosystem quality.

Comparing the sum effects of the collection sector and the treatment sector between the S2S and the CSS, the S2S obtains fewer score than the CSS in human health, ecosystem quality and climate change, but the former gains a higher score in resources. This is explainable. The

impacts of the both sanitation systems on human health, ecosystem quality and climate change mainly sources from their system running, while the resources consumption is mainly in infrastructural construction. Because the biogenic waste is reclaimed and reused, the running consumptions of the S2S in the collection and treatment sectors are less than those of the CSS. However, the S2S has one more logistic stream and more sophisticated appliance (vacuum kitchen refuse collector), so it consumes more resources in infrastructural construction than the CSS. In the collection sector of the S2S, the vacuum system contributes the most scores to each indicator, respectively as 60%, 62%, 63%, and 67% of human health, ecosystem quality, climate change and resources (See Table S6). Similarly, the biological digestion also contributes most damage scores in the treatment sector of the S2S. These are understandable, since the biogenic waste logistic stream of the S2S takes on most environment sanitation tasks of the whole system. In summary, San-2 has extraordinary advantages of environmental performance over Con-San, and this is mainly owing to its source-separation and resources reclamation property.

5.2 Sensitivity analysis

The inventory data showed in Table 3 are based on the average situations of Changshu area, and the parameters of the vacuum system are synthesized on the bases of the Hehuageng testing system and the expert consultants. The rural settling property may be various, and the predictions about the vacuum technology industry might be not exact. So it is necessary to check robustness of the abovementioned conclusions by changing the key parameters or assumptions of the application case. As shown in Table 4, seven scenarios in addition to the initial are set by changing seven parameters. All the scenarios are assessed by using the same method, and the results are presented in Figure 5, where each initial total score of the CSS is set as 100%.

Table 4 Description of the added scenarios.

	S0	S1	S2	S3	S4	S5	S6	S7
Settlement housing density	initial	×2						
Local settlement density	initial		×2					
Settlement population	initial			×0.5				
Vacuum electricity consumption	initial				×2			
Vacuum materials consumption	initial					×1.5		
Nutrient emission	initial						×0.5	
Biogas production	initial							No

The most significant characteristic of rural settlement is decentralization, which influences the difficulty and the costs of collective sanitations. The decentralization degree of the rural

settlement including housing density, distance between settlements and settlement population may be diverse in different regions. Comparing with S0, S1 doubles the each specific pipeline length per household for investigating the variation effect of the inside settlement housing density; S2 doubles the distance between settlement and farmland for investigating the effect of the distance between settlements; and for investigating the effect of settlement population, S3 assumes that to halve the settlement population will increase 20% consumptions of resources and energy. Figure 5 shows all indicator scores of the both systems in S1, S2 and S3 are larger than those in S0 because the more decentralized, the more resources and energy is needed. Generally, the relative increase of the each indicator score of the S2S is more than that of the CSS. The most decrease of the advantages lies in the resource indicator in S3 as shown in Figure 5(d), which score changes from 36.7% of S0 to 44.1% of S3, implying that the advantages of the S2S over the CSS will not be reversed in a large variation range of decentralization. Certainly, in case of extremely decentralized settlement, it will be unnecessary or uneconomic to build a very small or an insular S2S system, and some other type of sanitation (e.g. on-site Con-San or waterless toilet) may be a good complementary measure.

Vacuum source-separation is one core technology of San-2. S4 and S5 respectively increase 100% of the electricity consumption and 50% of the material consumptions. Certainly comparing with S0, the advantages of the S2S in all indicators become less, but they are still outstanding. The biggest loss of the advantages happens on the human health indicator in S4 (Figure 5(a)), and the relative score of the S2S to the CSS changes from 27.3% in S0 to 35.2% in S5. The advantage of the S2S over the CSS in ecosystem quality is the weakest among the all indicators. Volatile Ammonia emission in fertilization contributes most damage score to the ecosystem quality indicator. S6 halves the $\text{NH}_3\text{-N}$ emission rate of organic fertilizer. As shown in Figure 5(b), the relative score of the S2S to the CSS of ecosystem quality decreases from 54.0% of S0 to 31.1% of S6, meaning that performance of the S2S on ecosystem quality is sensitive to $\text{NH}_3\text{-N}$ emission of fertilization. Therefore, it is important for San-2 to develop low emission fertilization technology.

Fig. 5. Sensitivity analysis of key technical assumptions for seven scenarios

Different assessment methods may possibly lead to different LCA results, so ISO advises to check the robustness of the conclusions by employing the different environmental impact assessment methods. Therefore, the IMPACT 2002+, and ReCiPe method at midpoint level have been adopted to evaluate the studied systems. The results show the comparative impact scores of the both systems according to the eBalance, IMPACT 2002+, and ReCiPe method at midpoint level (Figure 6). All the results of the three methods obtain the same conclusions that the S2S presents remarkably lower potential environmental damage than the CSS for every indicator. In summary, the sensitive analysis illustrates that San-2 may hold its advantages over Con-San in comparatively wide ranges of the key parameter variations.

Fig.6. Comparative impact scores of the CSS and the S2S according to the different assessment methods.

5.3 Discussion

This study assesses the environmental performances of the studied sanitation systems throughout their life cycles basing on the best available foreground and background data and a recognized impact assessment method. It is aim to find a more sustainable and eco-environment friendly sanitation system, so the total environmental performance of the sanitation system is resolved into damage impact indicators of human health, ecosystem quality, climate change, and resources respectively, according to eight midpoint impact categories (ozone depression potential, respiratory inorganic, ionizing radiation, land use, acidification potential, eutrophication potential, greenhouse gas emissions and Chinese resource depletion potential).

The results show that S2S has significant advantages in human health, ecosystem quality, climate change and resources, compared to CSS. This conclusion runs counter to that reached in Thibodeau et al. (2014a, 2014b) in which the similar topic is dealt with when metal emission impacts from fertilizers are excluded. In this study, the study areas, household layout and infrastructure component are different from the urban areas and municipal sanitation system, which is the main possible reasons accounting for this phenomenon. However, Lam et al. (2015) obtained the similar conclusions that source-separation sanitation system got the best performance in terms of life cycle environmental impacts when addressing issues or poor sanitation and water scarcity in rural China. Therefore, the sanitation 2.0 system basing on vacuum source-separation is suitable for managing the rural waste and wastewater in China.

Some interesting findings can be extracted from the source analysis of environmental damage. The added process contributes the most impacts of the CSS for selected indicators, which directly implies the advantages of the S2S mainly come from its resources reclamation property. The by-product, such as biogas and organic fertilizer, of the S2S can reduce the consumption of electricity and chemical fertilizer, which would cause major environmental damages during the productive process. However, the S2S also pays for the resources reclamation for the indicators of ecosystem quality and resources. The termination sector of the S2S contributes 95% damage score of ecosystem quality because of the nutrients emissions of the organic fertilizer application. And the logistic stream and sophisticated appliance, such as the vacuum kitchen refuse collector, vacuum pump station, consumes more resources in infrastructural construction than the CSS in the collection sector. The technology of organic fertilizer production and application would be developed and improved so as to increase the fertilizer efficiency and reduce the emissions. People are forced to transfer the kitchen refuse from indoor to outdoor timely due to the high moisture of the waste. Therefore, it is possible to make the kitchen refuse collector into the common household appliances in future. If these happen, the superiority of environmental performances from S2S would become bigger.

Organic fertilizer is important useful product of the S2S with positive economic value. The existing literatures used to consider the effects of the reclaimed nutrition elements, e.g. N, P or K, equal to the same respective quantities of chemical fertilizers (Lam et al., 2015; Larsen et al., 2009; Thibodeau et al., 2014a, 2014b). However, this dealing largely underestimates the benefits of organic fertilizer. China succeeds to raises 22% of the global population with only 7% of the global farmlands, but she also consumes 35% of the global chemical fertilizer.

The specific N fertilizer application rate in China farmland is now about 4 times as the world average, but N use efficiency for crops is only about 30% -35% (International technology and economy institute development research center of the state council, 2006). Therefore, a conversion that 1 kg organic N equals to 2.035 kg chemical N, was employed to reflect the real benefits of organic fertilizer.

Sensitivity analysis gives the chances and direction to improve and develop the S2S to suit the different studied areas. Decentralization is a prominent aspect in rural areas. This study considers three factors of decentralization degree, such as pipeline length per household, the distance between settlement and farmland, and the settlement size. The result indicates that the extremely decentralized settlement is unnecessary or uneconomic to install the S2S. However, the critical point of decentralization degree couldn't be found because of complex factors, such as population mobility, geographical information, social and economic influences. Vacuum source-separation system mainly includes the vacuum toilet and vacuum kitchen refuse collector, one is an immature product and the other is a conceptual product. However, the consumption of the energy and materials from the vacuum facilities has little effect on the assessment. The economic aspect of the vacuum facilities may hinder the development and application in rural areas. The ammonia emission rate of the organic fertilizer, a conservative estimate from cattle slurry, is a significant factor to the ecosystem quality of the S2S. It could be determined more precisely considering the application method, the climate, the pH, the crop, and the properties of the soil and the period of application. These factors could be assessed through the framework of the current and the best spreading practices. Whether S2S has necessary to produce biogas during the anaerobic digestion depends on the local context of raw material, usability of biogas, and market factors.

6. Conclusions

This study develops a scheme of S2S facing the huge demands, questions and challenges of the Chinese rural environment sanitation. Basing on the analysis of the limitations of waterless toilet sanitation and a successful testing application case, vacuum source-separation is recommended as the best available technology for establishing the S2S. The advanced S2S system parts the whole regional rural waste and wastewater into three parallel logistic streams, of which the biogenic waste (toilet wastes and food residues) stream takes on the all sanitation, environment and resources tasks. A strategy that takes account of the unbalanced socio-economic condition is also advanced to develop region-scale S2S system. The advanced S2S scheme is studied basing on a simulating application case and the LCA method, and the results show that S2S has extraordinary advantages of environmental performance

over CSS, and the damage scores of the former are 27%, 54%, 27% and 37% as those of the latter with regarding the impacts on human health, ecosystem quality, climate change, and resources respectively in the Chinese context. Sensitivity analysis presents that the decentralization degree, the resource consumption of the vacuum facilities, and the production and application of by-product influence the environmental damage scores. The low decentralization degree, low ammonia emission rate and canceling biogas production can reduce the damage scores for the both systems. The ammonia emission rate and canceling biogas production are the key factor for the S2S, and the settlement population is the critical factor for the CSS.

Although the S2S have definite advantages in the environmental performances, these are not the whole benefits of S2S. The contemporary Chinese agriculture depending on chemical fertilizer has badly deteriorated the food quality and the farmland soil quality, which certainly impacts on health of human and creatures. One report of the Beijing Agriculture Committee said 60-70% of the leafy vegetables in Beijing markets have excess nitrate content, which in spinach was as high as 2358mg/kg (Cheng et al., 2010). These impacts need be studied and evaluated in future research. China is standing on the critical point that a modernized and pervasive rural environment sanitation management system should be established. Whether to follow the steps of the developed countries to select the CSS or to daringly develop and apply a more sustainable sanitation system is not a puzzle that is only in China. Therefore, the rural China and S2S are opportunity to each other.

The rural environment sanitation is a systematic work with extreme complexity, which is entangled with the questions of society, policy, economy and technology. The history of CSS is promoted by a gradual appeal from the individual sanitation to the public sanitation and now arriving at the global eco-environment, so the technology assembling vector of CSS had to adapt to this precedence order of interests. Generally, once the toilet format is fixed, the elemental technology principle of the whole sanitation system as well as the terminal treatment is almost fixed. Such an infrastructure system usually has a long life and need a big budget, so it is very hard to make big reform after the first step (e.g. the toilets). Chinese government starts to build the modern rural waste and wastewater management system for about half a billion people, much of which hasn't installed the conventional waster-flush toilets. It is time to consider and employ the S2S in rural China, which is also meaningful for the global sanitation development.

Acknowledgements

The research was financially supported by the Major Science and Technology Program for Water Pollution Control and Treatment of China (No. 2011ZX07301-003 and No. 2014ZX07204-005), the National Natural Science Foundation of China (No. 51278484 and No. 51308528), and the GCE of Bill-Melinda Gates Foundation (Opp1033932). We are deeply grateful to the reviewers and editor for their insightful and careful suggestions, which have greatly helped to improve the quality of manuscript.

Nomenclature

CLCD	Chinese Life Cycle Database
Con-San	Conventional sanitation
CSS	Conventional sanitation system
DN	Nominal diameter
LCA	Life cycle assessment
NRE	Nitrogen recovery efficiency
San-Agriculture	Sanitation agriculture
San-2	Sanitation 2.0
S2S	Sanitation 2.0 system
Si	Scenario i
SI Text	Supplementary Information Text
TEvap	Evapotranspiration tank

References

- Andersson, J.C., Zehnder, A.J., Wehrli, B., Jewitt G.P., Abbaspour, K.C., Yang, H., 2013. Improving crop yield and water productivity by ecological sanitation and water harvesting in South Africa. *Environ Sci Technol.* 47, 4341-4348.
- Bluteau, C.V., Massé, D.I., Leduc, R., 2009. Ammonia emission rates from dairy livestock buildings in eastern Canada. *Biosyst Eng.* 103(4), 480-488.
- Cheng, C., Shi, Y., Wen, T., 2010. The real costs of nitrogen fertilizers. Greenpeace. Available at www.greenpeace.org.
- China National Petroleum & Chemical Network, 2013. China Chemical Industry Yearbook (in Chinses).
- Duan, Y.H., Xu, M.G., Wang, B.R., Huang, J., 2010. Effects of long-term different fertilization on nitrogen recovery efficiency of maize in red soil. *Plant Nutrition & Fertilizer Science.* 16(5), 1108-1113 (in Chinses).
- Emmerson, R., Morse, G., Lester, J., Edge, D., 1995. The Life-Cycle Analysis of Small-Scale Sewage-Treatment Processes. *Water Environ J.* 9, 317-325.
- Flores, A.E., 2010. Towards Sustainable Sanitation: Evaluating the Sustainability of Resource-Oriented Sanitation. University of Cambridge, Cambridge, England.
- Gao, H., Zhou C.B., Li, F., Han, B.L., Li, X.X., 2016. Economic and environmental analysis of five Chinese rural toilet technologies based on the economic input–output life cycle assessment. *J Clean Prod.* 8(8), 91-8.
- Gao, J., Xu, M.G., Zhang, W.J., Zhang, S.X., Wang, B.R., 2009. Influences of long-term fertilizations on phosphorus recovery efficiency of wheat in six dry upland soils of China. *Plant Nutrition & Fertilizer Science.* 15, 584-592 (in Chinses).
- GIZ., 2012. Worldwide list of 324 documented ecosan projects by various organizations. Gesellschaft für internationale Zusammenarbeit (GIZ) GmbH, Eschborn, Germany. Available at www.susana.org/en/resources/library/details/1423.
- Grant, S.B., Saphores, J.D., Feldman, D.L., Hamilton, A.J., Fletcher, T.D., Cook, P.L., Stewardson, M., Sanders, B.F., Levin, L.A., Ambrose, R.F., Deletic, A., Brown, R., Jiang, S.C., Rosso, D., Cooper, W.J., Marusic, I., 2012. Taking the “waste” out of “wastewater” for human water security and ecosystem sustainability. *Science.* 337, 681-686.
- Greg, M., 2012. Getting minds out of the sewer. *Science.* 337, 679.
- Gretchen, N., 2012. Finding a new way to go. *Science.* 337, 673.
- Hou, J.W., Qu, B., Li, X.L., Fan, B., 2012. The Utilization Situation of Rural Biogas and Its Significance on Rural Domestic Wastewater Treatment: Example of Hebei and

- Shandong Province. China Biogas. 30, 47-51 (in Chinese).
- Hu, M., Fan, B., Wang, H.L., Qu, B., Zhu, S.K., 2016. Constructing the Ecological Sanitation: a Review on Technology and Methods. *J Clean Prod*, 125, 1-21.
- IEK, 2015. Full-featured LCA Software and Database Package -eBalance. Available at www.ike-global.com/archives/1097.html(accessed 11.05.15.)
- IKE, SCU-ISCP., 2013. Chinese core Life Cycle Database version 0.8. IKE Environmental Technology Co., Ltd. & Institute for Sustainable Consumption and Production at Sichuan University. Available at www.itke.com.cn.
- International technology and economy institute development research center of the state council, 2006. The situation analysis and suggestion of agricultural pollution in China (in Chinese).
- ISO I 14040, 2006: Environmental management—life cycle assessment—principles and framework. London: British Standards Institution.
- ISO I 14044, 2006: Environmental management life cycle assessment requirements and guidelines. International Organization for Standardization.
- Jenssen, P.D., Grottel, G.M., Warner, W.S., 2004. Sustainable Wastewater Management in Urban Areas. *Weiterbildendes Studium Wasser und Umwelt*. University of Hannover.
- Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Christie, P., Zhu, Z.L., Zhang, F.S., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences*. 106, 3041-3046.
- Lam, L., Kurisu, K., Hanaki, K., 2015. Comparative environmental impacts of source-separation systems for domestic wastewater management in rural China. *J Clean Prod*. 104, 185-198.
- Langergraber, G., Muellegger, E., 2005. Ecological Sanitation-a way to solve global sanitation problems? *Environ Int*. 31, 433-444.
- Larsen, T.A., Alder, A.C., Eggen, R.I., Maurer, M., Lienert, J., 2009. Source Separation: Will We See a Paradigm Shift in Wastewater Handling? *Environ Sci Technol*. 43, 6121-6125.
- Li, X.P., 2008. Study on phosphorus running off of paddy field in purple soil and its environmental impact (Ph.D. thesis). Southwest University, Chongqing, China
- Liu, L.Y., Cao, Y.S., Tian, Y.H., Yin, B., Zhu, Z.L., 2013. Ammonia volatilization and nitric oxide emission from soil during winter wheat season in Taihu Lake region. *Journal of Plant Nutrition & Fertilizer*. 19, 1420-1427.
- Ministry of Environmental Protection, 2014. Annual Statistic Report on Environment in

- China 2012, 2013 (in Chinses).
- National Bureau of Statistics, 2013a. China Energy Statistical Yearbook (in Chinses).
- National Bureau of Statistics, 2013b. China Industry Economy Statistical Yearbook (in Chinses).
- National Health and Family Planning Commission of the People's Republic of China, 2013. China Health Statistical Yearbooks (from 1999 to 2012) (in Chinese).
- Niero, M., Pizzol, M., Bruun, H.G., Thomsen, M., 2014. Comparative life cycle assessment of wastewater treatment in Denmark including sensitivity and uncertainty analysis. *J Clean Prod.* 68, 25-35.
- Oarga Mulec, A., Mihelič, R., Walochnik, J., Griessler Bulc, T., 2016. Composting of the solid fraction of blackwater from a separation system with vacuum toilets – Effects on the process and quality. *Journal of Cleaner Production.* 112, 4683-4690.
- Paulo, P.L., Azevedo, C., Begosso, L., Galbiati, A.F., Boncz, M.A., 2013. Natural systems treating greywater and blackwater on-site: Integrating treatment, reuse and landscaping. *Ecological Engineering.* 50, 95-100.
- Remy, C., 2010. Life Cycle Assessment of conventional and source-separation systems for urban wastewater management. Technische Universitaet Berlin, Berlin, Germany.
- Spångberg, J., Tidåker, P., Jönsson, H., 2014. Environmental impact of recycling nutrients in human excreta to agriculture compared with enhanced wastewater treatment. *Science of the Total Environment.* 493, 209-219.
- Statistical Bulletin of Urban-Rural Development, 2015. Ministry of Housing and Urban-rural Development of the People's Republic of China.
- Sunita, N., 2012. Sanitation for all. *Nature.* 486, 185.
- Thibodeau, C., Monette, F., Bulle, C., Glaus, M., 2014a. Comparison of black water source-separation and conventional sanitation systems using life cycle assessment. *J Clean Prod.* 67, 45-57.
- Thibodeau, C., Monette, F., Glaus, M., 2014b. Comparison of development scenarios of a black water source-separation sanitation system using life cycle assessment and environmental life cycle costing. *Resour Conserv Recy.* 92, 38-54.
- Ti, C.P., 2011. Regional nitrogen budget at different spatial scales (Ph.D. thesis). College of Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing, China.
- Todt, D., 2015. Source Separating Sanitary Systemse Energy Efficient Treatment of Blackwater and Minimizing Greenhouse Gas Emissions. Norwegian University of Life

- Sciences, Akershus, Norway.
- Tong, Y., Yao, R., He, W., Zhou, F., Chen, C., Liu, X., Lu, Y., Zhang, W., Wang, X., Lin, Y., Zhou, M., 2016. Impacts of sanitation upgrading to the decrease of fecal coliforms entering into the environment in China. *Environmental Research*. 149, 57-65.
- van Loosdrecht, M.C., Brdjanovic, D., 2014. Anticipating the next century of wastewater treatment. *Science*. 344, 1452-1453.
- Vogl, A., Bischof, F., Wichern, M., 2016. Single chamber microbial fuel cells for high strength wastewater and blackwater treatment-A comparison of idealized wastewater, synthetic human blackwater, and diluted pig manure. *Biochemical Engineering Journal* 115, 64-71
- Wang, X.D., Hu, T.T., Li, Q.X., Li, Z.Y., Zhang, Y.P., 2001. A Evaluation on the Phosphorus Component of Organic Materials and Its Phosphorus Supply Capacity. *Acta Agriculturae Boreali-occidentalis Sinica*. 10, 63-66 (in Chinses).
- Wendland, C., 2008. Anaerobic Digestion of Blackwater and Kitchen Refuse (Ph.D. thesis). Institute of wastewater management and water protection, Technical University of Hamburg-Harburg, Hamburg (Germany). Available at:http://doku.b.tu-harburg.de/volltexte/2009/553/pdf/wendland_dissertation_2009.pdf (accessed 27.05.11.)
- Winbald, U., Simpson-Hébert, M., 2004. Ecological sanitation-revised and enlarged edition. Coauthored by Calvert, P. et al. in 2004. Stockholm Environment Institute.
- Yan, X., Akimoto, H., Ohara, T., 2003. Estimation of nitrous oxide, nitric oxide and ammonia emissions from croplands in East, Southeast and South Asia. *Global Change Biol*. 9, 1080-1096.
- Zeeman, G., Kujawa, K., Meulman, B., Kwant, F., 2007. Full scale demonstration of vacuum collection, transport & treatment of black water, Poster presentation, Advanced Sanitation Conference, March 2007, Aachen, Germany.
- Zhang, J.F., She, Q.H., Chang, W.C., Tang, C.Y., Webster, R.D., 2014. Mining nutrients (N, K, P) from urban source-separated urine by forward osmosis dewatering. *Environ Sci Technol*. 48, 3386-3394.
- Zhao, L.P., 2009. Study on nitrogen and phosphorus losses of crop land through manure application under rainfall simulation condition (Ph.D. thesis). College of Resources and Environment, Huangzhong Agricultural University, Wuhan, China.
- Zhou, C., Liu, J., Wang, R., Yang, W., Jin, J., 2010. Ecological-economic assessment of ecological sanitation development in the cities of Chinese Loess Plateau. *Ecol Complex*.

7, 162-169.

Zhu, Z., 2008. Research on soil nitrogen in China. *Acta Pedologica Sinica*. 45(5):778-783.

Zhu, Z.L., Jin, J.Y., 2013. Fertilizer use and food security in China. *Plant Nutrition & Fertilizer Science*. 19, 259-273 (in Chinses).