Assessment of two faecal sludge treatment plants in urban areas: Case study in Beijing

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Abstract: Every day, human beings produce excreta all over the world, and the sludge that accumulates in waste disposal systems is referred to as the 'faecal sludge (FS)'. FS can cause serious environmental pollution in urban areas if it cannot be disposed of properly. A complete FS management system must include onsite sanitation technologies, FS collection and transport, a treatment plant, and resource recovery or disposal of the treatment end-products. Focusing on the treatment and reuse/disposal step of a FS complete service chain, this research presents two cases of FS treatment in Beijing. In Case 1, FS biogas plant adopts anaerobic digestion (AD) to treat FS, and the digestate can be used as biofertilizer in the surrounding greenhouse. In Case 2, several technologies including solid-liquid separation, dewatering, pyrolysis, AD and co-composting are integrated to find innovative solutions for FS treatment. A comprehensive assessment including the aspects of technology, economy and environment is conducted for further SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis. Then, critical strategies are developed, which include (1) selecting project site for optimized transportation, maximum waste reuse, minimum environmental impact and convenient final effluent disposal; (2) planning technical options at a feasible study stage, considering resource recovery, secondary pollution prevention and fire protection; (3) exploring market channels for by-products sale to increase profitability; (4) guaranteeing engineering quality and service life for the purpose of sustainable operation; (5) minimizing health risks to persons exposed to the untreated FS; and (6) providing necessary training for hygiene protection. The cases in Beijing can provide valuable lessons for urban areas in developing countries and the strategies can provide a reference for stakeholders and decision-makers who intend to develop FS treatment projects.

Keywords: faecal sludge, kitchen waste, composting, anaerobic digestion, SWOT
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1 Introduction

The wide-spread prevalence of unimproved sanitation technologies has been a major cause of concern for environment and public health. The sanitation needs of a worldwide population of 2.7 billion are served by onsite sanitation technologies, and the population is expected to grow to 5 billion by 2030[1,2]. The sludge that accumulates in onsite systems is referred to as faecal sludge (FS)[3]. Poor sanitation globally results in increased prevalence of diseases and pollution in the

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environment. Excreta, grey water and solid wastes are the major contributors to the pollution load into the environment and pose a risk to public health[4-6]. Promotion of hygiene might be the single most cost-effective way of reducing the global burden of infectious disease[7]. Over the past 30 years, the overlap of traditional and modern risks has been complicated by the largest ever migration of people from rural to urban areas[8]. Approximately 50% of people living in rural areas lack sufficient sanitation facilities, compared to only 18% of those in urban areas[9]. It is a common perception that onsite technologies fulfil sanitation needs for rural areas, but in reality, approximately one billion onsite facilities worldwide are in urban areas. In many cities, onsite technologies have much wider coverage than sewer systems[10].

With regards to China, the scenario is not optimistic, even though China has made great progress in the past decades. About 98% of the urban population in China had access to the improved toilets. The coverage of sanitary toilets in rural areas in China increased from 7.5% in 1993 to 76.1% in 2014[11]. Considering urban sanitation, the collected amount of urban FS is 15.46 million tons in 2014, among which 6.91 million tons were treated, accounting for a treatment ratio of 44.7%. Of all provinces and municipalities, Beijing led the nation in terms of a high treatment ratio of 91.4%[12]. Onsite sanitation technologies, such as septic tanks and ventilated improved pit latrines, each represent only one component in a comprehensive FS management system. As with sewer-based systems, a complete FS management system must also include FS collection and transport, a treatment plant, and resource recovery or disposal of the treated end-products[13]. Figure 1 shows a complete FS management service chain[14-16], where the final disposal/reuse is the key step for sustainable sanitation[17-20]. At the same time, human excrement represents a resource that could be better utilized as organic fertilizers and a source of biogas energy to improve environmental quality and promote human livelihood[21,22].

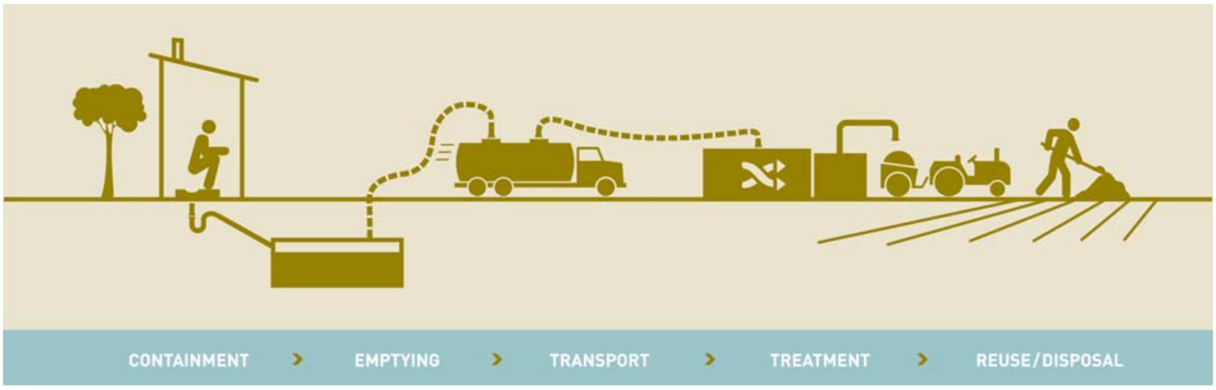

Figure 1 FS management service chain

Generally, strategic analysis and planning of the FS treatment project at the regional level can contribute to its implementation in a particular region in three aspects[23,24]. Firstly, it allows the government and industry stakeholders to further their understanding of the current FS treatment situation in the region under study. Secondly, it enables the identification of main problems that are faced by the construction industry, based on which effective measures can be presented for improvements. Finally, the analytic results can provide useful information to guide the development of FS treatment projects domestically or internationally in both short-term and long-term[25]. Therefore, this study aims at analysing a FS treatment project at the regional level in China. A SWOT (Strength, Weakness, Opportunity and Threat) analysis approach is employed to achieve the objective. The analysis is based on empirical investigations of two FS treatment plants in Beijing.

2 Materials and methods

2.1 Case scenarios

2.1.1 Case 1 – FS biogas plant

This plant is located in a village near Beijing International Airport, not far from the downtown area.

It receives ca. 20 t (average) FS per day, which is collected from the nearby public toilets. At the reception tank, a steel screening is used to remove bulk materials like toilet paper, plastic, etc. A homogenization mixer is installed in the centre of the reception tank. The heat for maintaining temperature comes from heating water to more than 70°C by 2-ring biogas burner, or with coal when biogas is insufficient or consumed in greenhouses. Before feeding, FS is pre-heated in a pasteurization batch basin (maintaining 70°C for some hours), which is covered and insulated, under slow mixing for sand precipitation. There is also a pre-heated water tank for circulation of the heating water, generated by solar panels. In addition to the main digester, another tank is used for storage of bio-slurry, which can also be treated as the secondary digester. A 200 m^3 biogas storage membrane is installed above the bio-slurry tank. The plant is adjacent to a greenhouse, so the use of bio-slurry is convenient. The final bio-slurry can be pumped to the greenhouse by means of an underground irrigation pipeline. Biogas can be used as a heat source for the digester insulation, feedstock disinfection, cooking fuel, greenhouses and for power generation if is needed[26]. Figure 2 presents the flow chart of Case 2.

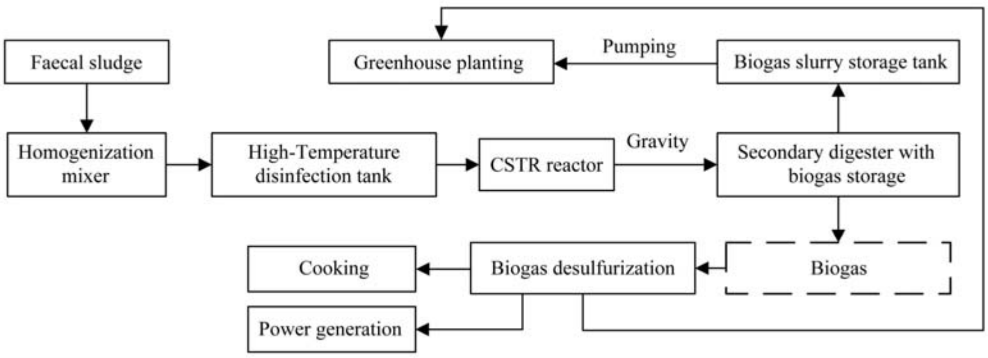

Figure 2 Flow chart of FS biogas plant

2.1.2 Case 2–FS and kitchen waste (KW) co-treatment plant

This plant is located inside the Changping Wastewater Treatment Plant (WWTP), north of Beijing municipality. It has been in operation since 2009 with a capacity of 300 t FS per day. In 2014, it was expanded and received another 50 t KW per day for co-treatment. For FS treatment, a screw shaft automatically separates large solids. After solid-liquid separation and dewatering by coagulation, the separated solid portion is divided in two parts. Organic solid sludge is acquired for further processing in a composting unit, and the nonorganic solid waste is disposed of in a landfill. The composting product is used for municipal greening. The liquid part of FS is pumped into a digester in which the effluent pollutant strength is further reduced and biogas is produced. For KW treatment, plastic bags are broken down, and the bulk waste is sorted out for landfill disposal. The screened organic portion is processed for pulping to 10 mm size. After a cyclone sand remover, the remaining KW is sent to a pyrolysis device for heating to up to 60°C-85°C. Then the effluent enters a three-phase separator to generate crude biodiesel for collection and selling as solid slag for landfills, and organic wastewater for anaerobic treatment. The effluent from digester enters another wastewater treatment unit before it goes into the nearby Changping WWTP. Moreover, most units are built inside a room for odor control. The collected odor is treated by bio-filter made of wood before vented into air. Figure 3 presents the flow chart of Case 2.

2.2 SWOT application

This study first makes a comprehensive assessment of both cases, and then explores the SWOT. The SWOT methodology is the current standard methodology used for position audits and strategic planning. It is a two-step process. Firstly an audit of SWOT themes relevant to the development of the entity under study is carried out, and then a strategic development model is constructed by matching the internal strengths and weaknesses of the entity to external environmental opportunities and threats[27-30].

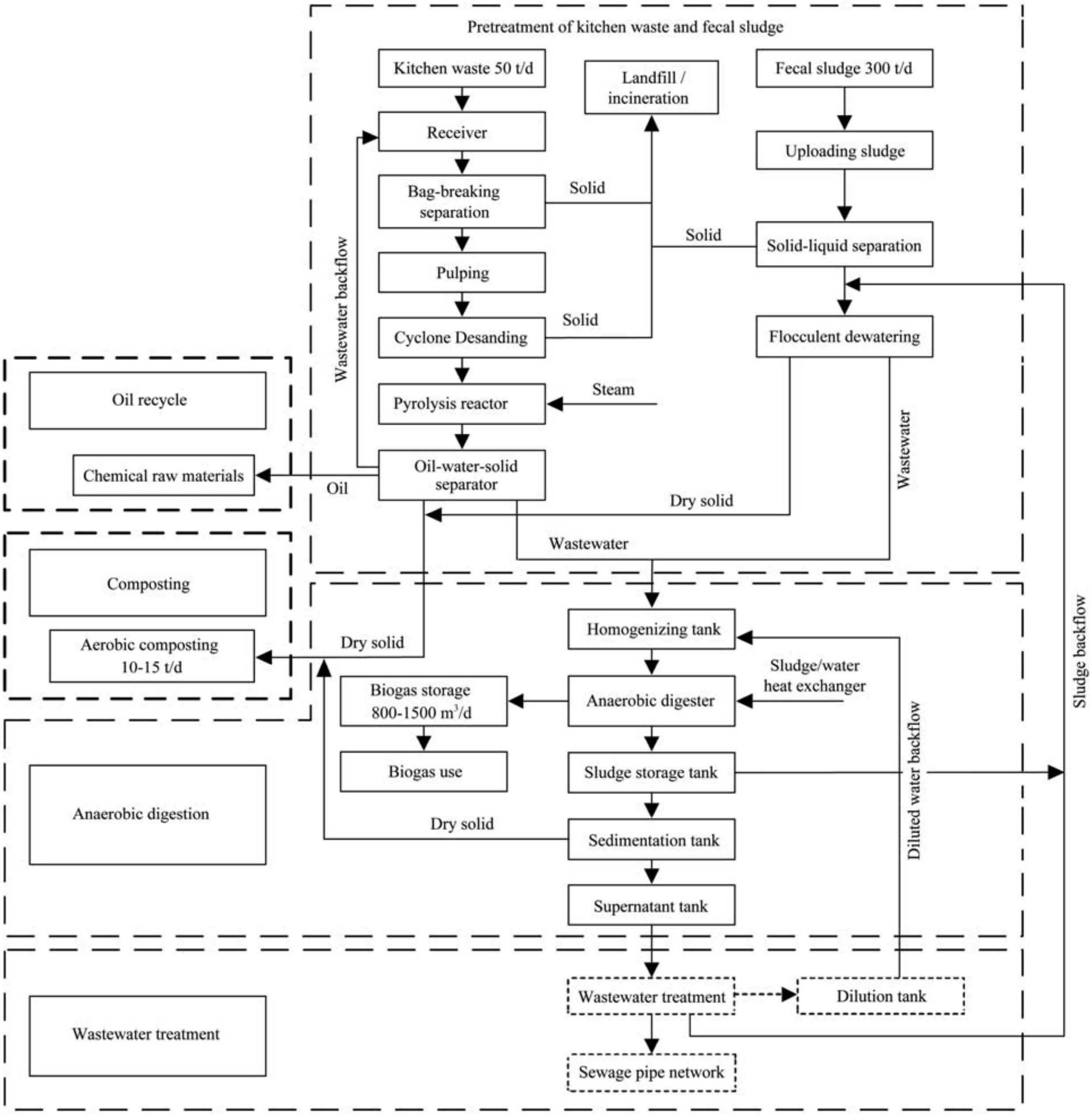

Figure 3 Flow chart of faecal sludge and kitch waste (FS-KW) co-treatment plant

3 Results and discussion

3.1 Comprehensive assessment

3.1.1 Technical assessment

From the technical aspect, the two case studies employ the typical FS treatment technology for proper disposal[31]. Case 1 adopts anaerobic digestion (AD) technology for biogas production. Unlike other agricultural biogas plants, FS needs to be disinfected before feeding in order to kill pathogens, which is a potential threat to bio-slurry. Other than pasteurization, other components of the flow chart are similar to typical agricultural biogas plants for animal manure disposal. Digestate biofertilizer from the AD of FS can be used to improve soil fertility[32]. The flow chart of Case 2 is complex, which adopts dewatering, pyrolysis, co-composting, AD, etc. Co-composting of FS with other biomass (e.g., saw dust, mushroom substrate) is implemented with sludge that has undergone dewatering. After dewatering, FS has a moisture level of 18% while other biomass has a moisture level of 40%-60%. Therefore, typically not much additional moisture can be added before the system gets too wet. It has been proven that dewatering and co-composting can contribute to inactivating pathogens[33,34]. The detailed technical parameters for both cases are shown in Table 1.

Table 1 Technical parameters for both cases

	Case 1	Case 2
Feedstock	ca. 20 t FS per day	300 t FS per day + 50 t KW per day
Core technology	Pretreatment + disinfection + AD	Separation + pyrolysis + pulping + coagulation + composting + AD + wastewater treatment (Anaerobic +Oxic+ MBR)
Digester	CSTR, mesophilic, 400 m^3 (main digester) + 225 m^3 (digestate storage tank as secondary digester) Dry matter: 3.0%-3.5% Retention time: 20 d	CSTR, thermophilic, 180 m^3×2 Retention time: 2 d
Disinfection	Pasteurization at 70°C	Pyrolysis device for heating up to 60°C-85°C, composting
Output	Biogas + bio-slurry	Biodiesel + composting + biogas
Fertilizer	Bio-slurry storage and distributed to nearby greenhouse.	Aerobic dynamic composting Final product: 10-15 t/d One period: ca. 15 d; 6 d more than 50°C in the centre, natural self heating, only additional heating to prevent frosting of equipment in winter time
Biogas	200-400 m^3/d, stored by integrated digester and used for insulation, disinfection, cooking	800-1500 m^3/d, use for disinfection and others directly burned by biogas torch
Biodiesel	-	2-3 t/d Three-phase separation: oil (biodiesel) + wastewater + dreg (solid)
Effluent	Reuse nearby in greenhouse	180 t/d to WWTP for final treatment
Odor control	Almost no	Sealing + wooden bio-filter
Mechanization	Manual sorting	Automatic separation

3.1.2 Economic assessment

Case 1 belongs to the village committee which has no access to municipal management. In such a case, the government levies neither discharge fees for final effluent emission nor disposal fees for faecal sludge. The truck is operated by the sanitation department of the government to transport the FS to the site without paying or being paid. There is only one staff member who is in charge of the operation and maintenance. The revenue mainly comes from the production of organic vegetables or fruits by means of using bio-slurry as fertilizers. This part is incomputable. Case 2 is an Engineering Procurement Construction (EPC) model project which is owned and operated by the local government. A private company is in charge of the design, construction, equipment, etc. The disposal fees for FW and KW are the main revenue which can provide a reasonable income. Equipment cost accounts for more than half of the capital investment. The plant is subsidized by the government and the compost is not sold as a commercial product, but rather is used only for municipal landscape greening. The current level of guaranteed tariffs can cover associated expenses. In light of initial investment, the two cases are not on the same level due to distinguishing disposal capacity and equipment. Buy rough calculation, the net income of Case 2 is about 7.278 million CNY/a without consideration of unexpected costs. In addition, when the gate fee of KW and FS decreases or the selling of biodiesel is not at the high price, the revenues will be reduced considerably. For Case 1, the benefit is mainly from bio-slurry application in greenhouse, even without charge. The lessons learned from this experience illustrate that in low-income countries, vast improvements in sanitation can be affordable when FS management is employed, whereas sewer based systems are prohibitively expensive, and unreachable in most situations.

Table 2 Economic data of two cases

		Case 1	Case 2
Capital investment		2 million CNY	30 million CNY
Operation cost	Transport cost for collecting feedstock	No charge	1.6 million CNY/a
	Electricity consumption	100 000 CNY/a	1.75 million CNY/a
	Water consumption for cleaning	5000 CNY/a	175000 CNY/a
	Maintenance	20 000 CNY/a	300 000 CNY/a
	Labour	24 000 CNY/a (1 person)	1.44 million CNY/a (30 persons)
Discharge fee	Final effluent	No charge	197 000 CNY/a
Revenues	Disposal fee of KW	No charge	4.18 million CNY/a (229 CNY/t)
	Disposal fee of FS	-	4.92 million CNY/a (45 CNY/t)
	Biodiesel	-	2.92 million CNY/a (4000 CNY/t)
	Fertilizer	Self-use	Self-use
	Biogas	Self-use	Self-use

Note: 1 USD=6.7763 CNY, Bank of China, 11/11/2016.

3.1.3 Environmental assessment

Historically, human excreta or FS, can have long-term use in agriculture[35]. However, if FS is not properly disposed, it will result in hygiene issues among the local population[36]. Both plants in this study properly maintain final effluent. While utilizing WWTP and greenhouse there is no concern for secondary pollution to the environment. Odor is an arrestive issue for a FS treatment plant. The FS treatment plant in Case 1 does not focus on the odor issue, so there is heavy odor near the reception and disinfection tanks. By contrast, Case 2 controls the odor well, which is collected and emitted out via bio-filter tank filled with woody pellets. FS contains large amounts of microorganisms mainly originated from the faeces. The microorganisms can be pathogenic, and exposure to untreated FS constitutes a significant health risk to humans, either through direct contact, or through indirect exposure. Case 1 adopts pasteurization for hygiene but workers are exposed to the odor, which has a potential impact on human health. Case 2 takes measures in discharging FS. A reception pipe is connected with trucks without leakage, and the floor is flushed clean by tap water immediately after FS discharging. In Case 2, the quality of compost and equipment are tested monthly by the environmental department. An example of the testing results is shown in Table 3 which shows that the quality of compost meets the national standard of GB 8172-87 Control Standards for Urban Wastes for Agricultural Use.

Table 3 Test results of composting product from cast 2

Item	Unit	Limited value	Test result
pH	-	6.5-8.5	7.85
Cd	$mg \cdot kg^{-1}$	≤3	0.617
Total arsenic	$mg \cdot kg^{-1}$	≤30	10.553
Total chromium	$mg \cdot kg^{-1}$	≤300	116
Total mercury	$mg \cdot kg^{-1}$	≤5	0.907
Water content	%	25-35	7.33
Pb	$mg \cdot kg^{-1}$	≤100	6.22
TN	%	≥0.5	1.13
TK	%	≥1.0	0.876
TP	%	≥0.3	1.13
Total organic matter	$mg \cdot kg^{-1}$	-	42.67
Volume-weight	$mg \cdot m^3$	-	388
Faecal escherichia coli	$No. \cdot kg^{-1}$	-	<9000
Mortality of helminth eggs	%	95-100	Not detected

3.2 SWOT analysis

SWOT analysis of the FS treatment project helps further the understanding about both the external and internal conditions in developing such projects. Particularly, the internal conditions are related to the strengths and weaknesses and the external conditions refer to the opportunities and threats. In order to validate the SWOT analysis, we conducted onsite observation and face-to-face interviews with a diverse group of experts, including regional policy makers, representatives from interest groups, project designers and operators of projects. A real time account of these SWOTs (see Table 4) identified from results of the focus group meeting is provided below.

Based on the SWOTs identified above, critical strategies for development of FS treatment project can be proposed accordingly, which is exhibited in Table 5. Firstly, site selection must be convenient for transportation, waste reuse, final effluent disposal, etc. Site selection must be far away from densely inhabited districts in order to bring less impact to nearby residents. Furthermore, measures should be taken for odor control as in the FS treatment project. There are some media reports about neighbouring residential complaints, which indicate the importance of site selection and odor control. Secondly, the planning should be carefully taken into consideration, and the technology should be proven to avoid secondary pollution. Resource recovery should be maximally integrated into the whole process. The most common resource recovery from FS has been the compost as a soil conditioner and organic fertilizer, as excreta contain essential plant nutrients and organic matter that increases the water retaining capacity of soil. However, there are several other treatment options for resource recovery. For example, biogas can be produced during anaerobic digestion of FS, while the remaining sludge also being used as a soil conditioner. FS treatment can be combined with other waste disposal methods to recover end products as a biofuel. For example, via pyrolysis, gasification, incineration and co-combustion or as a resource of organic matter recovery through the growth of Black Soldier flies can be used for protein production[37-40]. Thirdly, market channels should be explored. Financial and political implementations account for some of the reasons that FS management systems have not been widely implemented. Government subsidies would be the main motivation for such project implementation in the short term. The sale of by-products may compensate only part of the operation cost. Stakeholders would like to see a preferential policy to pursue subsidies in the form of waste handling fees. Fourthly, sustainable operation of FS treatment projects should be highlighted. Corrosion takes place frequently within a short term (3 years) in Case 1, and the replacement of equipment is difficult. It is suggested that project owners should contract with equipment providers or general contractors for life service of the project. Given that the quality of equipment is varied, a related standard of equipment should be established. Additionally, the bio-slurry cannot be reused in a greenhouse over a period of time due to the confliction between plant owners and greenhouse owners concerns about land use, which should be determined initially. Lastly, exposure to the untreated FS constitutes a significant health risk to humans, either through direct contact, or through indirect exposure. Staff who has access to the FS treatment facility should be trained in hygiene protection.

Table 4 Results of SWOT analysis of both cases

Case 1- FS biogas plant	Case 2- FS and KW co-treatment plant
Strengths	
● Good location – built next to greenhouse for bio-slurry and biogas reuse. ● Combining waste treatment with agricultural production. ● Replacing chemical fertilizer with biogas slurry. ● Relative low investment. ● Safe agricultural production – the vegetable and fruit are planted in the way of green food or organic food. ● Need few staff - only one person operates.	● Co-treatment of FS and KW. ● Good location – built inside of WWTP, which can receive the final effluent of FS and KW after treatment. ● Production of biodiesel, composting, biogas. ● Good control of odor – the treatment unit is sealed with air-tight door. ● Most units are controlled automatically. ● Considerable handling fee.
Weaknesses	
● No control of odor - heavy odor from disinfection unit by heating - ammonium emissions. ● No subsidy from municipal government. ● Corrosion issues after few years operation - leakage of biogas. ● Hazardous potential from unclean biogas –desulfurizing agent is out of function after long time operation without replacement. ● Low use of biogas – hardly use of power generation and direct emission of biogas sometime.	● Low use of composting product – only for municipal greening. ● Need more people to operate and maintenance. ● Long flow chart– process is complex, which needs relative senior technicians. ● Government-owned plant without marketing of output. ● Most biogas is burning without reuse. ● High investment – more equipment and truck arrangement.
Opportunity	
● Toilet revolution requires complete FS service chains that highlight the treatment and reuse. ● This model can be copied where FS treatment can be integrated with agriculture production. ● Organic food production with bio-slurry. ● Off-season production with a high selling price.	● Toilet revolution requires complete FS service chains that highlight the treatment and reuse. ● This model is can be copied in the metropolis worldwide where population density is high. ● New industry and employment creation. ● Rapid urbanization and increase of KW for treatment.
Threats	
● Regulatory and policy uncertainty - difficulty in obtaining project finance. ● Greenhouse land ownership - conflicts between biogas plant (village government) and greenhouses (recently privately owned). ● Sorting of paper are handled manually –sanitation and hygiene issue. ● Low energy saving – need more fuel (coal) for heating digester in winter. ● Integration into energy supply markets (current use of biogas restricted by access to heat demands and energy markets).	● Limited occupied areas – concentrated treatment unit, resulting in safety issue. ● Lack of market experience – no market for composting and biodiesel. ● Lack of standards on FS and KW equipment ● Planning and licensing requirements ● Lack of processing facilities for wastes (Need to facilitate separate collection of food waste). ● Possibility of resident complaint if improper odor control.

Table 5 Strategies for successful development of FS treatment project

	Strengths	Weaknesses
Opportunities	● Reasonable site selection to reduce environmental impact and transportation optimization. ● Integrating FS treatment with resources recovery to explore by-product production and high value-added products. ● Stimulating development of new industry and employment creation.	● Reasonable planning at feasible study stage – considering biogas utilization and fire protection. ● Guaranteeing engineering quality and service life for sustainable operation. ● Reasonable handling by-products to avoid secondary pollution.
Threats	● Clarifying land use to avoid the breakdown of by-products utilization chain. ● Identifying regulation and policy on subsidy/handling fee to obtain finance support. ● Formulating related standards of equipment.	● Hygiene protection for working staff who may potentially access to FS treatment. ● Odor control for environmental protection and residential complaint. ● Exploring market channel for by-products sale to increase the profitability.

4 Conclusions

Two cases of FS treatment in Beijing were studied from the technical, economic and environmental viewpoints. It was found that finding innovative ways to create viable business opportunities, such as co-treatment with KW, biodiesel production, bio-slurry application in greenhouses, in sanitation is considered a promising pathway for improvements in this sector.

SWOT analysis was conducted on both cases to conclude the following critical strategies for development of a FS treatment project: (1) selecting project site for optimized transportation, maximum waste reuse, minimum environment impact and convenient final effluent disposal; (2) planning technical options at a feasible study stage, considering resource recovery, secondary pollution prevention and fire protection; (3) exploring market channels for by-products sale to increase the profitability; (4) guaranteeing engineering quality and service life for the sake of sustainable operation; (5) minimizing health risk to persons who are exposed to untreated FS; and (5) providing necessary training to workers with regard to hygiene protection.

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