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Modeling Decentralized Source-Separation Systems for Urban Waste Management

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***Abstract*—**Decentralized eco-sanitation system is a promising and sustainable mode comparing to the century-old centralized conventional sanitation system. The decentralized concept relies on an environmentally and economically sound management of water, nutrient and energy fluxes. Source-separation systems for urban waste management collect different solid waste and wastewater streams separately to facilitate the recovery of valuable resources from wastewater (energy, nutrients). A resource recovery centre constituted for 20,000 people will act as the functional unit for the treatment of urban waste of a high-density population community, like Singapore. The decentralized system includes urine treatment, faeces and food waste co-digestion, and horticultural waste and organic fraction of municipal solid waste treatment in composting plants. A design model is developed to estimate the input and output in terms of materials and energy. The inputs of urine (yellow water, YW) and faeces (brown water, BW) are calculated by considering the daily mean production of urine and faeces by humans and the water consumption of no-mix vacuum toilet (0.2 and 1 L flushing water for urine and faeces, respectively). The food waste (FW) production is estimated to be 150 g wet weight/person/day. The YW is collected and discharged by gravity into tank. It was found that two days are required for urine hydrolysis and struvite precipitation. The maximum nitrogen (N) and phosphorus (P) recovery are 150-266 kg/day and 20-70 kg/day, respectively. In contrast, BW and FW are mixed for co-digestion in a thermophilic acidification tank and later a decentralized/centralized methanogenic reactor is used for biogas production. It is determined that 6.16-15.67 m^3/h methane is produced which is equivalent to 0.07-0.19 kWh/ca/day. The digestion residues are treated with horticultural waste and organic fraction of municipal waste in co-composting plants.

***Keywords*—**Decentralization, ecological sanitation, material flow analysis, source-separation

I. Introduction

SUSTAINABLE urban waste management integrates both solid waste and wastewater of urban area by converting different waste streams into valuable resources. This proposal challenges the conventional century-old activated sludge system, landfilling and incineration. The conventional system collects different waste streams in centralized treatment facilities to control pollution and ensure public health [1]. However, the sustainability of this system has been questioned with emerging global issues, such as energy and water shortage [2], depletion of phosphorus sources [3], eutrophication of water bodies [4], and heavy metal contamination [5].

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On the contrary, the decentralized system proposes source-separation with treatment of different waste streams. The concepts of decentralization in environmental management involve the local community with flexibility in varying site conditions [6]. Ideally, with the increment of population density, the cost per capita (including construction and maintenance) of decentralized system is constant, whereas the cost per capita of centralized system decreases exponentially [7,8]. Therefore, at certain population density, a balanced point of cost per capita will be met between decentralized and centralized system. EPA study [9] suggests that both centralized and decentralized systems could be balanced up for small communities and areas on the fringes of urban areas (i.e. decentralized cluster system). In a long term, decentralized system is believed as a more sustainable system with less waste transport, recovery of nutrients, materials and energy. However, the ecological balance point between both systems is difficult to be investigated [1].

Ecological sanitation (EcoSan) is a closed-loop sustainable concept that can be found in decentralized wastewater system [10]. This concept has been practiced with an increasing number of case studies from rural, peri-urban and urban areas [11]. Source-separation into grey water, yellow water, brown water or black water with nutrient and energy recovery starts from the design of toilet. The conventional flushing toilet is replaced by low-water vacuum-toilet, low-water separating toilet, waterless urinal or waterless composting toilet in EcoSan [12]. The conventional toilet is criticized as ecological mindless as the design itself goes against the laws of nature [13,14].

Black water (urine, faeces and flush water) together with less-polluted grey water (washing and cleaning water) is transported to centralized activated sludge system. The produced sludge is then dewatered before being sent to anaerobic digester, land application or incineration plants [5]. The flush water which acts as a transport agent of human waste and cleaning agent of toilet bowl is heavily polluted by 0.55 to 2.2% of human waste [15]. Furthermore, nitrogen and phosphorus removal become more difficult after large dilution of yellow water. Grey water that can be easily treated for reuse is mixed with other waste streams. In short, clean water, chemicals and energy are wasted in the conventional wastewater system.

The objective of this study is to evaluate a decentralized source-separation system for urban waste management in Singapore. For this purpose, it is developed a model involving the inputs and outputs of energy and materials for a neighbourhood size in Singapore.

II. Method

Material Flow Analysis (MFA) is one of the most fundamental ways of analyzing a process or system processes [16]. This analysis is based on two main principles: system approach and mass balance. It is a prerequisite for the successful use of another analytical tool, such as Life Cycle Assessment (LCA) [17].

The inventory of materials is obtained from two approaches according to the following priority: experimental data based on local conditions, then references with some justifications from similar studies. Design model is developed by using Microsoft Excel 2007 to estimate the input and output of different waste streams. Daily energy generated per capita is estimated at the end of analysis.

Based on ISO 14040 guidelines for Life Cycle Assessment, three main processes for MFA can be expressed as:

1. Goal and system definition
2. Inventory and modeling
3. The interpretation of results (environmental impacts are excluded in this study)

III. Goal and System definition

This system is modeled for Singapore's 20,000 population high-density residential neighbourhood in year 2012. The modeling sizes of similar studies are compared in Table I.

TABLE I
Comparison with similar LCA studies

Similar LCA studies	Country	Year	Population
LCA of municipal waste water systems [18]	Sweden	1998	900 & 12,600
System analysis for environmental assessment of urban water and wastewater system [16]	Sweden	2002	15,000
Ecological Assessment of Ecosan concept and conventional wastewater systems [19]	Germany	2003	4,000,000
LCA of conventional and source separation systems for urban wastewater management [5]	Germany	2010	5,000
This study (proposed)	Singapore	2012	20,000

There is a population size gap between 2002 and 2003 study. The conclusion of 2002 study states that the environmental impact superiority for both centralized and decentralized system is difficult to justify. A slightly higher population (20,000) is therefore suggested for future investigation in economical and environmental assessment. In addition, this figure falls into the estimated range of a population between 9,867 and 50,240 per neighbourhood in Singapore [20,21].

Each neighbourhood is served by a self-contained cluster of neighbourhood shops, primary schools, clinics and community centers. Several dwelling units share small game courts or children playground forming a "precinct" [21].

This neighbourhood model comprises 5 precincts and each precinct contains 10 dwelling units. Each dwelling unit is 20-storey high with 100 housing units of 4 occupants on average.

IV. Inventory and Modeling

The material flows of yellow water, brown water, food waste, horticultural waste and grey water are shown in Figure 1.

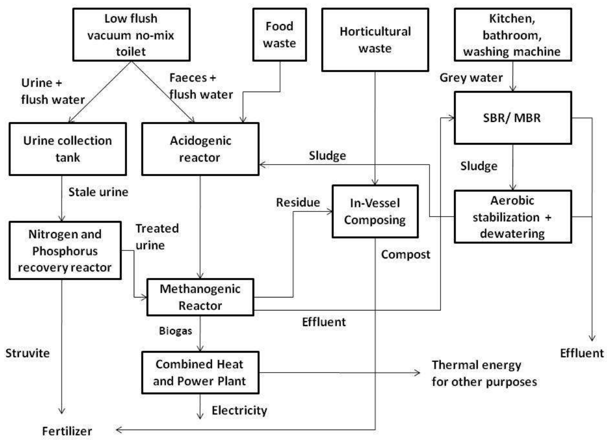

Fig. 1 Material flows in proposed decentralized system
(SBR = Sequence Batch Reactor; MBR = Membrane Bioreactor)

In this study, only yellow water, brown water and food waste are analyzed (grey water and horticultural waste are excluded). Inventory of nutrient recovery in yellow water is listed in Table II.

TABLE II
Inventory of nutrient recovery in yellow water

Inventory	Value	Unit[A]
Urine of an adult at home	0.4-0.8 [22,23]^	L/(ca·d)
Dry weight of adult urine	25-35 [24,25]^	g/(ca·d)
Frequency of urination	4-6 (5.6) [26]	/(ca·d)
Flushing volume for urine	0.2^	L
Contact time for complete ureolysis	2[#]	d
Urine separation efficiency of toilet	60-90 [27]	%
Nitrogen-N of urine (dry weight)	15-19 [24,25]	%
Maximum Nitrogen-N recovery rate from urine	100^	%
Phosphorus-P_2O_5 of urine (dry weight)	2-5 [24,25]	%
Maximum Phosphorus-P_2O_5 recovery rate from urine	100^ (98) [28]	%

[A]L= litre, ca=capita, d=day, g=gram, %= percentage; [#]Experimental result; ^ Justification is needed

Yellow water and brown water are separated by using a no-mix vacuum toilet. The flushing water is around 0.2 litre per flush for urine and 2.5 L per flush for faeces. The target toilet model, which is still not available in market, is able to separate urine and faeces by gravity and vacuum technology, respectively. Meanwhile, the modified flushing water of urine and faeces are 0.2 L and 1 L, respectively. Compared to 6 L flushing water of conventional gravity toilet, 94% drinking water quality of daily flushing water is saved.

Both struvite precipitation and ammonia stripping are grouped as "Nitrogen and Phosphorus (NP) recovery reactor". The processes can be completed within 1 day. The maximum Nitrogen and Phosphorus recovery rate, i.e. 100%, are estimated here. The actual recovery rates will be investigated through pilot studies.

By estimation, volume and dry weight of urine and faeces produced at home is reduced by half comparing to daily production in literatures. Inventory for the co-digestion of food waste and brown water is listed in Table III.

TABLE III
INVENTORY OF CO-DIGESTION FOR BROWN WATER AND FOOD WASTE

INVENTORY	VALUE	UNIT[A]
Frequency of defecation	1 [29]	/d
Dry weight of faeces	34-40 [30,31]^	g/ca/d
Volume of adult faeces	0.11-0.19 (0.18) [31]^	L/ca/d
Flushing volume for faeces	1^	L
Household food waste (wet weight)	150^	g/ca/d
Bulk density of food waste	514 [32]	kg/m^3
Moisture content of food waste	75-80 [33]	%
HRT of substrates in acidogenic reactor	2-4#	d
HRT of substrates in methanogenic reactor	15-20#	d
Volatile solid reduction of substrates after acidogenesis	30 [33]	%
Biogas production per volatile solid removal	450#	L/kg
Total volatile solid removal	60-70#	%
Methane content in biogas	60#	%
Energy content of methane	10 [34]	kWh/m^3
Conversion into heat energy in Combined Heat Power (CHP) plant	50 [35]	%
Conversion into electrical energy in Combined Heat Power (CHP) plant	35 [35]	%

[A]L= litre, ca=capita, d=day, g=gram, kg=kilogram, m^3=cubic metre, %= percentage, kWh=kiloWatt-hour; #Experimental result; ^ Justification is needed.

There is no local representative study of household food waste. A small-scale food waste study [36] shows that every occupant produces 129 grams household food waste (wet weight) only. Compared to a representative study from the UK [37], the average food waste per British in 4-occupants households is 246 grams. A study by Remy [5] suggests 160 grams as a good reference. Singaporeans seldom cook at home; therefore, an estimation of 150 grams is used for household food waste.

Through experiments, it was found that a hydraulic retention times (HRT) 2 to 4 days for acidogenesis and 15 to 20 d for methanogenesis is required. The biogas production volume is 450 L per kg volatile solid removal. Compared to Chia [33], the biogas production volume is 300-330 L per kg volatile solid removal if food waste is used as sole feed. Therefore, brown water enhances biogas production.

V. INTERPRETATION OF RESULTS

The effective volumes of several reactors are estimated in order to design the corresponding served size for each reactor. Every dwelling block is served by a urine collection tank to hydrolyze urine and minimize the occurrence of pipe clogging. A dwelling block with an input range of 20-42.2 kg/d (dry weight) is designed for each acidogenic reactor. In order to reduce manpower, the output from acidogenic reactor is delivered to methanogenic reactor then combined heat power (CHP) plant that serve a neighbourhood. The Volatile Fatty Acids-rich effluent from NP recovery reactor will serve as an extra source for methanogenic reactor as well. The details for each reactor are presented in Table IV.

TABLE IV
DESIGNS OF IMPORTANT REACTORS WITH SERVED SIZES AND ESTIMATED EFFECTIVE VOLUMES

REACTOR	PURPOSE	SERVED SIZE	ESTIMATED EFFECTIVE VOLUME (M^3)[A]
Urine collection tank	To store yellow water for natural ureolysis and sterilization	1 dwelling block (400 occupants)	0.83-1.54
Acidogenic reactor	To convert organic substrates into volatile fatty acids (VFAs)	1 dwelling block (400 occupants)	1.12-2.37
Methanogenic reactor	To convert VFAs into biogas for energy generation	1 neighbourhood (20,000 occupants)	439.93-631.32

NP recovery reactor is in continuous flow. [A]m^3=cubic metre

The small estimated effective volume of urine collection tank and acidogenic reactor enables them to be allocated at the void deck of every dwelling block. However, an open space is needed for methanogenic reactor in every neighbourhood due to its estimated volume of 439.93-631.32 m^3. Apart from space consideration, aesthetics, odor control, system maintenance and internal security are the key factors in the design phase. The useful outputs and their substitutions of this model are listed in Table V.

TABLE V
QUANTITY OF USEFUL OUTPUTS AND THEIR SUBSTITUTION

USEFUL OUTPUT	QUANTITY[A]	SUBSTITUTION
Methane	6.16-15.67 m^3/h	Imported natural gas
Electricity	0.03-0.07 kWh/ca/d	Electricity from centralized power plant
Thermal energy	0.04-0.09 kWh/ca/d	Electricity to heat water
Harvest of NH_3-N	7.5-13.3 g/ca/d	Mineral fertilizer
Harvest of PO_4^{3-}-P	1.0-3.5 g/ca/d	Mineral fertilizer

[A]ca=capita, d=day, g=gram, m^3=cubic metre, kWh=kilo-Watt-hour

Two outputs are not included in this study. First, solid residues of methanogenesis and horticultural waste will be co-composted into fertilizer occasionally. Second, liquid effluent from methanogenesis will serve as an inflow of further treatment.

Figure 2 shows a detailed diagram of daily material flows analysis for a neighbourhood within the system boundary. Accordingly, the electricity and thermal energy produced from biogas utilization is 518-1316 and 740-1880 kWh/day respectively. The electricity can be used in public facilities like street lamps and ventilation system in car parks. The thermal energy can be used for heating shower water, etc. The organic fertilizer can be shared as a community property in non-agricultural society of Singapore.

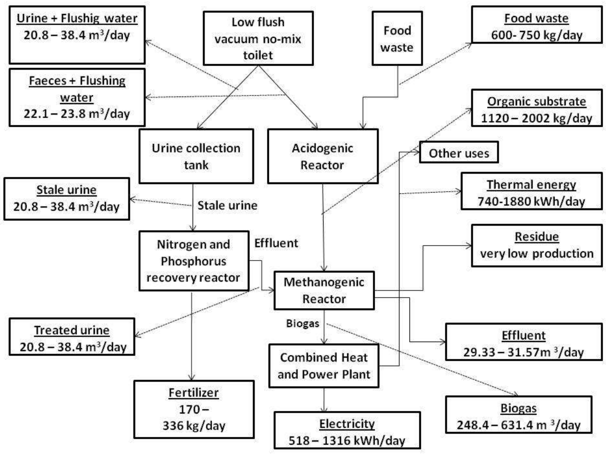

Fig. 2 Material flow analysis for a neighbourhood within system boundary

VI. Conclusion and Overview

Decentralized source-separation system has a potential application in high population density community of Singapore. The material flow of yellow water, brown water and household food waste are analyzed with known and justified parameters. The effective volumes of reactors are designed in line with the planning of Singapore Housing and Development Board (HDB). The optimum scenario has to be determined by pilot scale experiments to produce the maximum electricity per capita per day.

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