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RESEARCH ARTICLE

Sustainable design of sanitation system based on material and value flow analysis for urban slum in Indonesia

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Abstract Material flow analysis (MFA) and value flow analysis (VFA) were applied to the sanitation system in an urban slum in Indonesia. Based on the results of the MFA and VFA, garbage and excreta disposal costs were evaluated to be 0.7% and 1.1%, respectively, of per capita income. Such value flows seem reasonable in light of the recognized affordability to pay (ATP) standard. However, current excreta disposal methods create negative impacts on downstream populations. Because such disadvantages do not go back to disposers, but passed to downstream, the current value flow structure does not motivate individual toilet users to install treatment facility. . Based on current material and value flow structures, a resource recycling sanitation system scenario was examined. Based on VFA, an affordable initial cost for such a system was calculated; this was found to be comparable in price to a cheaper composting toilet that is currently available in the market.

Keywords material flow, value flow, resource recycling system, sustainable design, initial cost, urban slum

1 Introduction

Highly populated urban areas require large material inflows of food for people. Although this incoming materials is consumed, it does not disappears, because waste materials is generated, which needs to be disposed of in some manner, mainly as solid waste and as waste water, including toilet waste water. If the urban system does not introduce systems to manage these material outflows, unfavorable wastes accumulate in the urban area or flow to unfavorable locations, such as into surface and grand water reservoirs, both of which are usually important water sources. Such problems can be observed in many developing countries [1–3], and although it is recognized that solutions to such problems are needed, investment in outflow systems tends to be given lower priority because they do not have clear direct benefits, unlike projects such as production, supply, and transportation.

On the other hand, sustainability has recently been recognized as important factor for societies system. Several types of resource recycling toilets and wastewater treatment systems for reuse have been proposed as sustainable sanitation system technologies [4–6]. Although these technologies have the advantage, that they can create value from unwanted waste, they need to be embedded in system designed suitably to manage equipment outflow. It is therefore important to understand current and future material flows in and around targeted urban areas. Material flow analysis (MFA) or substance flow analysis (SFA) are suitable methodologies for this purpose. The application of the MFA to sanitation systems has been attempted in several studies, some of which considered sanitation systems as a part of material flows [7,8], and some of which focused mainly on sanitation system [9,10]. However these studies describe current material flows and only providing the conceptual description of possible improvements.

In an actual application, the optimization of the material flow design is not sufficient to drive the system. Successful material flow programs needs to be designed such that they benefit all stakeholders and incorporate well planned value chains. Therefore, it is believed that both material flow and value flow should be considered simultaneously. In this study, material flow is attempted to be related with value flow for designing sustainable sanitation systems for a slum area in Bandung, Indonesia, which have been studied comprehensively.

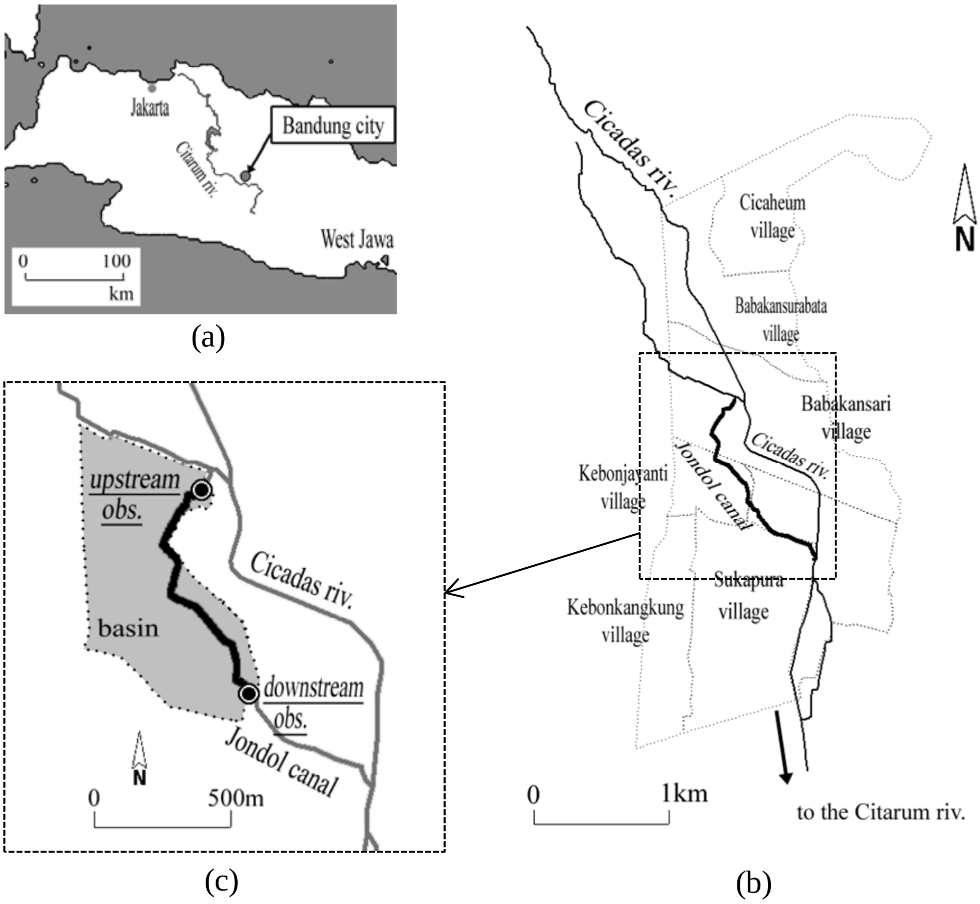
2 Materials and methods

2.1 Overview of study site

Bandung is the fourth largest city in Indonesia, with a population of 2.5 million [11]. It is in the inland part of west Java and is located upstream of the Citarum River, a major source of water for the capital, Jakarta (Fig. 1(a)). Only 16% of the domestic wastewater generated in Bandung City is treated, as the city has only one treatment plant, located in the suburbs [12]. The Kiaracondong sub-district is located near the center of

Bandung city, and is known as the city’s largest slum. According to 2006 local statistics, Kiaracondong has a population of 116000 living within an area of 6.1 km^2.

Two types of field surveys were conducted. One was conducted in the Jondol Canal [13], which flows through central Kiaracondong into the Cicadas River, which is a tributary of the Citarum River. In the area surveyed, there were no houses connected to the sewerage system feeding the treatment plant. Figure 1(c) shows the measurement locations and catchment of the studied section of the Jondol Canal, with a distance of 960 m between the two observation sites. This area of the catchment was measured to be 0.41 km^2 and, as determined by previous investigations and local statistics, has a population of 16240 people and 3585 households. The other survey was conducted in the Jondol Canal catchment area. In this survey, sixty-two families living near the canal were interviewed about their water use, their wastewater disposal, and other related matters [13].



(a)

(c)

(b)

Fig. 1 Location of studied area: (a) location of Bandung City; (b) Kiaracondong Sub District; (c) observatories and catchment

2.2 Data sources

The results of field surveys on river water [13], domestic wastewater [13,14], and garbage disposal and collection [15], in addition to official statistics for Indonesia [16], were used as the main data.

2.3 Methods

MFA and SFA were used to analyze current and future sanitation systems from a comprehensive and practical viewpoint. The subjects covered in the MFA included excrement as well as all related materials, namely, water and food. The SFA was conducted along a similar framework, focusing on nitrogen and phosphorus which, as major components of fertilizers, are important factors in resource recycling systems. When data for the slum area were unavailable, data from statistics and literature on Indonesia or other South-east Asian countries were used for extrapolation. The project boundary was set as the catchment area described in Fig. 1(c). All the data were expressed in terms of per capita years, because both material and value flows are discussed together in this study and the use of such unit is meaningful to the study of value flow.

MFA and SFA were also used for estimating value flow. In contrast to material and substance flows, value flow can be measured in a number of ways. Some can be definitely measured in quantitative factors such as prices or monetary value, whereas some can be only evaluated in qualitative factors, such as status or comfort derived. In this study, the quantitative values were evaluated based on the available data, whereas qualitative values were simply determined to be positive or negative by assessing the directions of material and value flows.

Material, substance, and value flow analysis were conducted for two scenarios: one representing current conditions, and the other assuming the implementation of a resource recycling sanitation system involving the installation of a urine diversion aerobic composting toilet [17] in each household. The framework proposed and discussed quantitatively by Ushijima [14] for the collection of urine and compost for integration with existing garbage collection systems, wherein organic solid waste is processed in a composting toilet along with feces, was applied.

Successful diffusion of this resource recycling system primarily depends on each household’s decision of whether to install the composting toilet. This decision is based on the following criterion:

$$(\textit{Initial cost} \,/\, \textit{expected lifetime}) < (\textit{WTP for excreta disposal}) + (\textit{income from selling excreta}), \qquad (1)$$

where WTP is “willingness to pay”. Here, *WTP for excreta disposal* is estimated by

$$(\textit{WTP for excreta disposal}) = (\textit{Current excreta disposal cost}) + (\textit{Initial cost for water flush toilet} \,/\, \textit{expected lifetime}), \qquad (2)$$

where the *Current excreta disposal cost* is equal to the sum O_c11+O_c12, given in Table 1

Table 1 Mass, Phosphorus, Nitrogen and value of each arrow in current material flow

ID	supplied item	mass	P	N	value	data source
		/(kg·(year·capita)$^{-1}$)			/(Rp·(year·capita)$^{-1}$) /(% against income)	
I_c1	water	32000	0	0	+ 110000 (2.8%)	mass, value: average of 3 households in Ushijima[14]. P, N: regarded as ignoreable
I_c2	food	170	1.3	6.0	+ 1400000 (35.9%)	mass, value: Gunawan[16], P, N: blackwater + solid waste
I_c3	electricity	0	0	0	+ 170000 (4.4%)	value: average of 3 households in Ushijima[14], mass, P, N: meaningless
O_c1	blackwater	14000	1.2	5.9	± 0 (0%)	mass: $I_c1 \times 0.41$[14] + O_c11 + O_c12, P, N: O_c11 + O_c12
O_c11	feces	33	0.3	0.9	–13000 (0.3%)	mass, P, N: Ushijima[14], value: water consumption for defecation (water cost × percentage of water use for defecation)
O_c12	urine	370	0.9	5.0	–32000 (0.8%)	mass, P, N: Ushijima[14], value: water consumption for urination (water cost × percentage of water use for urination)
O_c2	graywater	19000	1.0	0.0	± 0 (0%)	mass: I_c1-O_c1, P, N: total wastewater (maximum in Ushijima [14]) - O_c1
O_c3	solid waste	67	0.1	0.2	–28000 (0.7%)	mass: Ushijima [14], P, N (unit): Aramaki & Thuy [8], value: collection fee (Ushijima [14])
O_c31	junk material	(no data)	0	0	+	P, N: non-organic is regarded as 0
O_c32	solid waste	(no data)	0.1	0.2	-	D3–D31
O_c33	junk material	(no data)	0	0	+	P, N: non-organic is regarded as 0
O_c34	accumulation	(no data)	0.1	0.2	-	D32–D33
O_c4	work force	0	0	0	+ 3900000 (100%)	mass, P, N: meaningless value: average of 3 households in Ushijima[14]
R_c1	river inflow	52000	0.4	1.3	± 0 (0%)	Ushijima[14], N: NH_4-N + NO_2-N + NO_3-N P: PO_4-P
R_c2	river outflow	110000	1.2	3.5	± 0 (0%)	Ushijima[14], N: NH_4-N + NO_2-N + NO_3-N P: PO_4-P
R_c3	mosque	8300	0	0	± 0 (0%)	Ushijima[14]

3 Results

3.1 Current material flow

Figure 2 shows current material flows. Total mass flow, phosphorus mass flow, nitrogen mass flow, and total value flows are summarized in Table 1. Note that several value flows, namely, I_c21, I_c22, I_c23, I_c24 and I_c25 were not quantified in this study.

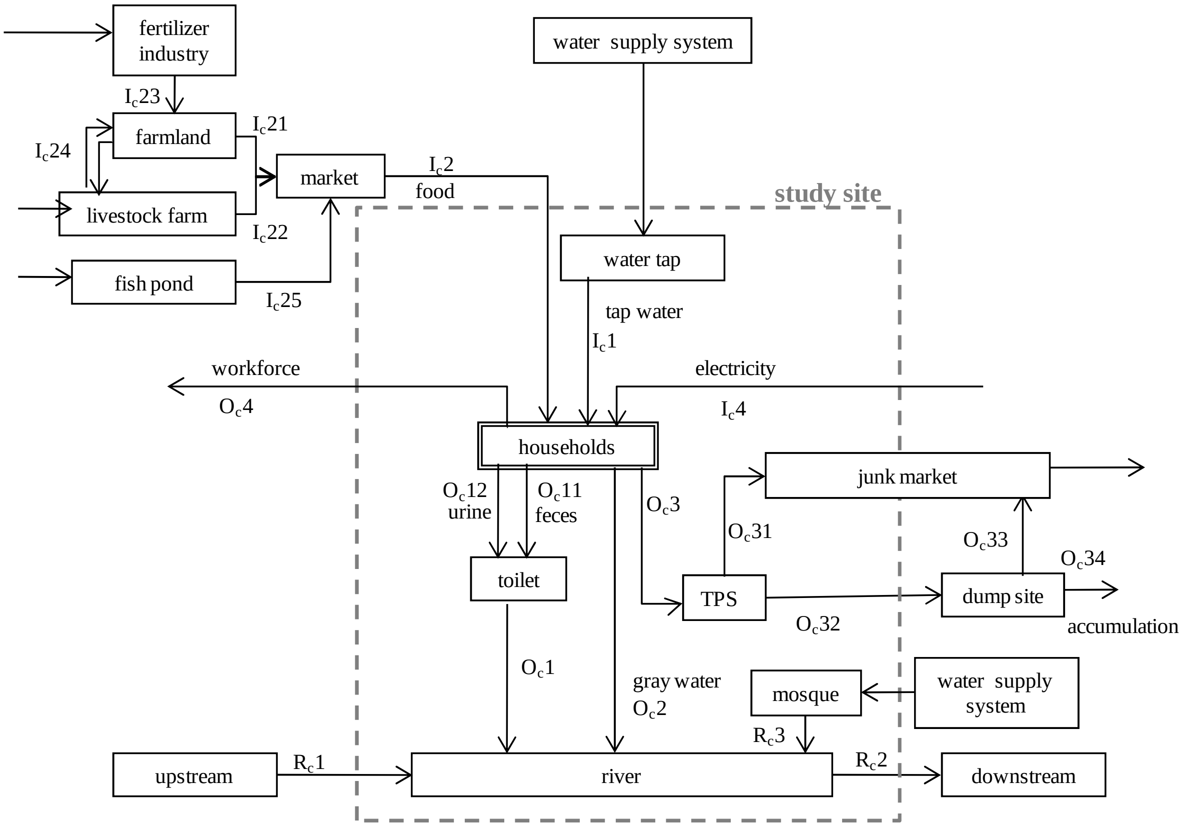


Fig. 2 Current material flow

3.2 Material flow of resource recycling sanitation system

Figure 3 shows material flows under a future scenario in which a resource recycling sanitation system is applied. Total mass flow, phosphorus mass flow, nitrogen mass flow, and total value flows are summarized in Table 2. Note that several mass flows, namely, I_r21, I_r22, I_r23, I_r24, and I_r25 were not quantified in this study.

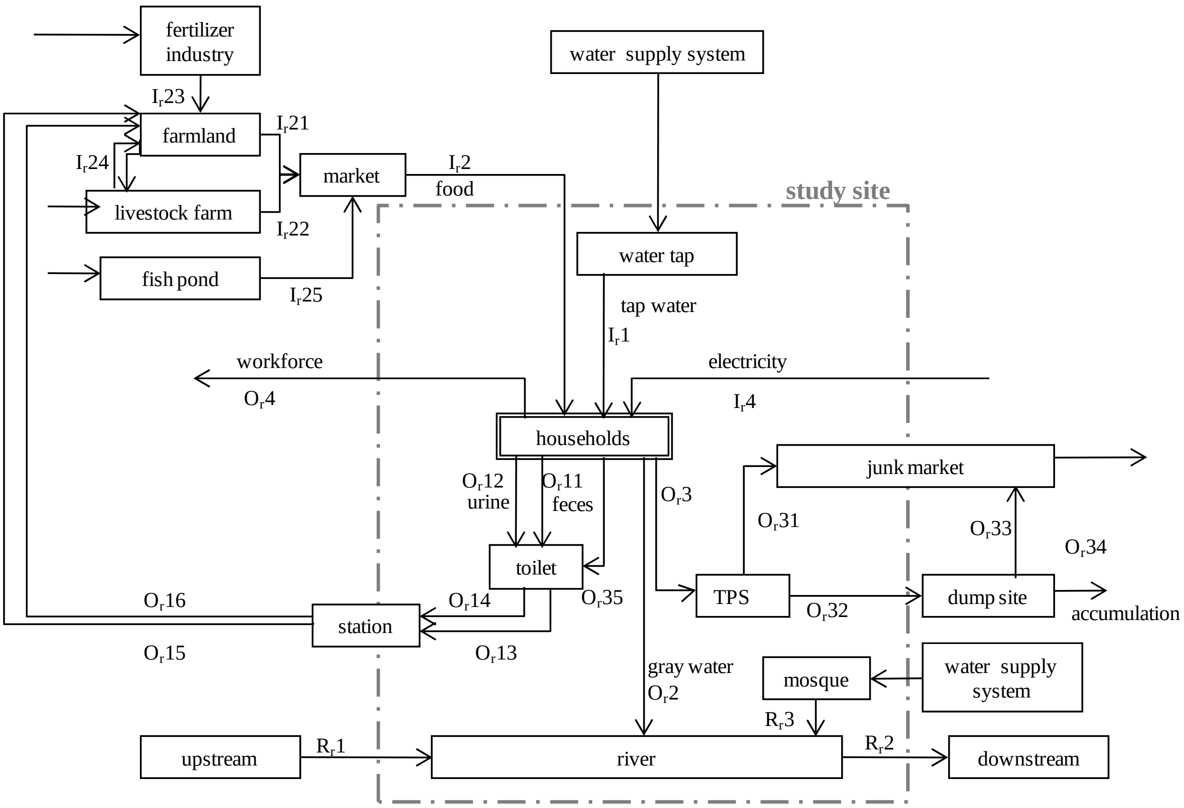


Fig. 3 Material flow of resource recycling scenario

Table 2 Mass, phosphorus, nitrogen and value of each arrow in material flow of resource recycling sanitation system.

ID	supplied item	mass/	P/	N/	value/	data source
		(kg·(year·capita)$^{-1}$)			(Rp·(year·capita)$^{-1}$) (% against income)	
I_r1	water	32000	0	0	+ 110000 (2.8%)	mass, value: average of 3 households in Ushijima[14]. P, N: regarded as ignoreable
I_r2	food	170	1.3	6.0	+ 1400000 (35.9%)	mass, value: Gunawan[16], P, N: blackwater + solid waste
I_r3	electricity	0	0	0	+ 170000 (4.4%)	value: average of 3 households in Ushijima[14],mass, P, N: meaningless
O_r11	feces	33	0.3	0.9	variable	mass, P, N: Ushijima[14], value: water consumption for defecation (water cost × percentage of water use for defecation)
O_r12	urine	370	0.9	5.0	variable	mass, P, N: Ushijima[14], value: water consumption for urination (water cost × percentage of water use for urination)
O_r13	processed feces	variable	0.3	< 0.9	variable	P, N: = O_r11
O_r14	processed urine	variable	0.9	< 5.0	variable	P,N: = O_r12
O_r15	collected feces	variable	0.3	< 0.9	variable	P, N: = O_r11
O_r16	collected urine	variable	0.9	< 0.9	variable	P, N: = O_r12
O_r2	graywater	19000	1.0	0.0	± 0 (0%)	mass: I_c1-O_c1, P, N: total wastewater (maximum in Ushijima [14]) - O_c1
O_r3	solid waste	17	0.0	0.0	–28000 (0.7%)	mass: Ushijima[14], P, N: non-organic is regarded as 0, value: collection fee (Ushijima[14])
O_r31	junk material	(no data)	0	0	+	P, N: non-organic is regarded as 0
O_r32	solid waste	(no data)	0.0	0.0	–	D3–D31
O_r33	junk material	(no data)	0	0	+	P, N: non-organic is regarded as 0
O_r34	accumulation	(no data)	0.0	0.0	–	D32–D33
O_r35	organic waste	50	0.1	0.1	+	mass: Ushijima [14], P, N (unit): Aramaki & Thuy [8]
O_r4	work force	0	0	0	+ 3900000 (100%)	mass, P, N: meaningless, value: average of 3 households in Ushijima [14]
R_r1	river inflow	52000	0.4	1.3	± 0 (0%)	Ushijima[14],N: NH_4-N + NO_3-N P: PO_4-P
R_r2	river outflow	97000	0.8	3.5	± 0 (0%)	Ushijima[14], N: NH_4-N + NO_3-N P: PO_4-P, reaching ratio of N, P: 0.36
R_r3	mosque	8300	0	0	± 0 (0%)	Ushijima[14]

4 Discussion

4.1 Current material flow

Using material flow and value flow analysis, the value flow in and around an urban slum family were analyzed, not only in terms of easy-to-price factors or quantitative flows but also in terms of difficult-to-price factors or qualitative flows, such as garbage disposal and excreta disposal. Based on the result, “costs for disposal” for garbage and wastewater were determined. These values, listed in Table 1 are approximately 0.7% and 1.1% of per capita income for garbage disposal and for urine and excreta disposal, respectively. The World Bank has roughly evaluated benchmarks for affordability to pay (ATP) as 2% and 1% of consumable per capita income for garbage collection service and sewerage service, respectively [18], similar to the current costs derived here. Thus, current value flows for garbage and excreta disposal seem reasonable for people in light of such benchmarks. However, the material flow of excreta into the river is clearly causing deterioration of the water environment. Because this value loss has a negligible direct effect, and because the disadvantages apply to populations downstream instead of to disposers, it would seem that the structure of the current value flow would impede efforts to improve the water environment.

4.2 Resource recycling system

A proposed resource recycling sanitation system would not discharge excreta to the river; rather such waste would be sent to farms, where it would have positive value as a fertilizer. From the catchment area studied, the system would remove almost all the nitrogen and half of the phosphorus discharged, and therefore, the net flux of nitrogen and phosphorus through the river under a recycling scenario (see Fig.3: R_r2–R_r1) would be less than under current conditions (Fig.2: R_c2–R_c1). The positive impacts on river water quality resulting from the introduction of resource recycling sanitation would be potentially large.

As it is a source of nutrients, excreta has good potential for the generation of value through use as fertilizer. However, the value of compost made from human excreta may also be discounted relative to chemical fertilizers because of psychological resistance. Further, the quality or handling of the processed excreta may also affect the value of the resulting compost. However, the price of synthetic fertilizers has been rising the last decade, and if this rise continues, the incentive of saving costs through substitution may overcome the psychological barriers.

In any event, the exact value of human excreta is currently difficult to evaluate. A case study of one company selling liquid fertilizer made from human urine seems suitable as a reference [19]. The company pays 1000 Rupiah$\cdot$L^{-1} to people as compensation for urine offer. Assuming that one liter of urine is produced per capita per day, this price corresponds to 365000 Rupiah$\cdot$(capita$\cdot$year)$^{-1}$, equivalent to 9% of per capita income, which is listed in Table 1 as O_c4.

In the area studied, the initial cost of a water flush toilet is reported to be approximately 2000000 Rupiah [14]. Assuming a family size of four people and a toilet lifetime of 15 years (which is standard in Japan), the WTP is thus estimated at 79000 Rupiah·(capita·year)$^{-1}$. If we apply the excreta price mentioned above as an optimum estimation, affordable initial cost for resource recycling sanitation system is estimated as

$$(\textit{Initial cost} / \textit{lifetime}) < 4400000 \text{ Rupiah}\cdot(\text{capita}\cdot\text{year})^{-1}, \tag{3}$$

For a 15-year lifetime composting toilet, the estimated affordable initial cost for a four person family would be 27000000 Rupiah, equivalent to approximately 3200 USD according to the June 2011 exchange rate. This is similar in price to a cheaper composting toilet (approximately 2000 USD) currently available in the market.

5 Conclusions

In this study, for an urban slum, the material and value flows of water, sanitation related materials, nitrogen, and phosphorus were calculated and plotted. The value flow analysis evaluated garbage disposal cost and excreta disposal cost at 0.7% and 1.1%, respectively, of household income, which represents a reasonable cost to disposers. However, under the current disposal scheme, negative value due to excreta disposal appears to be passed on to downstream populations. The structure of this value flow suggests that little attention is paid to the negative externalities, indicating that a solution in this case may be difficult to obtain.

The affordable initial cost of a new resource recycling system was evaluated and compared with the costs of a currently used commercial compost toilet by evaluating equipment lifetimes and potential income streams available from the sale of human excrement fertilizers. To estimate a value for the human excrement fertilizer, real-world case study in Indonesia, in which money was paid in exchange for human urine, was referred to. The evaluated affordable initial cost derived was sufficiently comparable to the price of a cheaper composting toilet currently available in the market. This implies that such a resource recycling system is feasible even in an urban slum.

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