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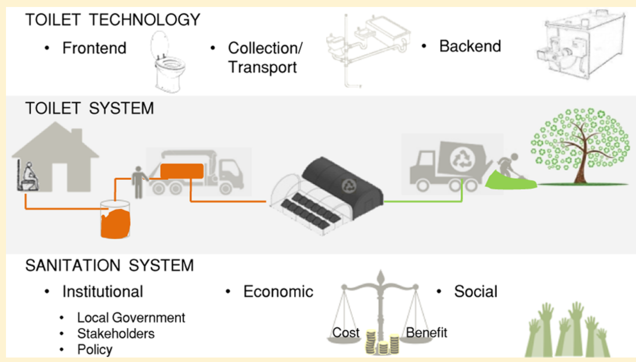
Ensuring Sustainability of Non-Networked Sanitation Technologies: An Approach to Standardization

Markus Starkl,*,† Norbert Brunner,‡ Magdalena Feil,§ and Andreas Hauser§

†University of Natural Resources and Life Science, Gregor Mendel Strasse 33, A-1180 Wien, Austria
‡CEMDS, Gregor Mendel Strasse 33, A-1180 Vienna, Austria
§TÜV SÜD Asia Pacific Pte Ltd, 3 Science Park Drive, Singapore 118223

Supporting Information

ABSTRACT: Non-networked sanitation technologies use no sewer, water or electricity lines. Based on a review of 45 commercially distributed technologies, 12 (representing three concepts) were selected for a detailed audit. They were located in six countries of Africa and Asia. The safety of users was generally assured and the costs per use were not excessive, whereas costs were fully transparent for only one technology surveyed. A main drawback was insufficient quality of the byproducts from on-site treatment, making recycling in agriculture a hygienic and environmental risk. Further, no technology was sufficiently mature (requiring e.g. to shift wastes by hand). In order to promote further development and give producers of mature products a competitive advantage, the paper proposes a certification of technologies to confirm the fulfillment of basic requirements to make them attractive for future users.



1. INTRODUCTION

1.1. Background. Sanitation in developing countries resembles the situation in developed countries during the early 20th century, when sanitation was a challenge for health policy even in rich countries. For instance, in the U.S. in 1935 "water carriage of sewage was a great step in advance" but researchers asked that it should be followed by adequate wastewater treatment.[1] For developed countries the solution was the flush toilet based sanitation system with end of pipe wastewater treatment.

Also developing countries took conventional sanitation as a model for their development. But there are huge costs to overcome the sanitation crisis[2] and connect a growing population to new sewer lines and treatment plants: About 32−36% of the global population (estimate[3] for 2015) lack household-level access to safe water or hygienic toilets. This led to compromises. For instance, "improved sanitation" (WHO and UNICEF definition) does not require end-of pipe treatment. In developing countries 1.5 billion people (in addition to those without adequate sanitation) use sanitation systems, which do not protect the wider population from exposure to human excreta.[4]

What systems are appropriate for a rapid up-scaling that keeps pace with population growth in developing countries, if "using flush toilets with piped sewage in such places would be unwise", considering expensive or lacking treatment at the end of the pipe.[5] This question is not new: Already in 1971 it was asked, if modern technology could devise a better method of sewage disposal than using drinking water (which gets scarce) to transport human waste away from the bathroom; the proposed dry toilet was primitive, but foreshadowed modern developments.[6] A rethinking at larger scale started toward the new millennium, supporting policies for water reuse, nutrient recycling, and renewable energy. It led to a redesign of toilets, for example, for nutrient recycling by urine separation, or for energy recovery by biogas toilets. Further, compost (e.g., composting toilets) was proposed against soil degradation in semiarid climates.[7]

However, there is still no widely accepted alternative to conventional sanitation. In 2011 the Bill and Melinda Gates Foundation (BMGF) started the "reinvent the toilet challenge". The focus was on the poor, whose toilets should cost less than five cents per user per day and have additional benefits by recovering valuable resources (energy, clean water, nutrients). In order to be independent of municipal infrastructure, toilets should avoid connection costs and operate "off-the-grid" without connections to water, sewer, or electrical lines. Toilets should have an attractive design, being desirable also in rich countries, and they should be safe for health and free of appalling odor.

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A number of industries, companies, NGOs, and research institutes have been developing, commercializing and applying non-networked toilet solutions. While these toilets work well for demonstration projects, their relevance for sanitation practice may be limited due to technical, geographical, cultural or legal reasons. In developing countries for such reasons also "supposedly successful systems on close inspection turned out to fail".[8] This paper therefore asks how to make innovative toilets successful. A major problem is the diversity of technologies, which makes them difficult to compare, whence the reasons for success and failure do not easily generalize. Also publications with objective and critical evaluations are not always based on the same standards. Entrepreneurs supporting innovative toilets would need such information to avoid stranded investments; also more risk-averse utilities and city managers may be unwilling to implement undocumented innovative toilets.

1.2. Goal. The paper aims at setting a framework for standards and certificates based on the assessment of impacts on health and the environment under consideration of economic, social, cultural and institutional aspects. In order to (1) assess the information needs of decision-makers, who evaluate and finally implement non-networked sanitation technologies, and to (2) identify possible issues, when different types of toilets are compared by uniform standards, 12 toilet systems in Sub-Saharan Africa, South Asia, and East Asia, representative for three technological concepts, were evaluated. This comparison was not intended to identify a "best technology" or to prove that non-networked technologies would be better or worse than conventional ones.

Producers requested commercial confidentiality. Therefore, technologies are not described in detail, their exact location is not disclosed, and performance details serve only illustrative purposes.

2. APPROACH AND DATA

2.1. Systems Approach. A *systems approach* (Figure 1) has been chosen. The paper distinguishes between toilet technologies, toilet systems, and sanitation systems. *Toilet technologies* refer to the frontend of the toilet, its collection and transport system; and to the backend only insofar, as it is delivered with the toilet. A *toilet system* refers to a toilet technology together with the backend. A *sanitation system* encompasses the entire sanitation chain, from the point of excreta generation through collection, transportation, treatment and safe use of treated material; it includes the economic, social and institutional context of the toilet system. The following system components and processes have been identified.

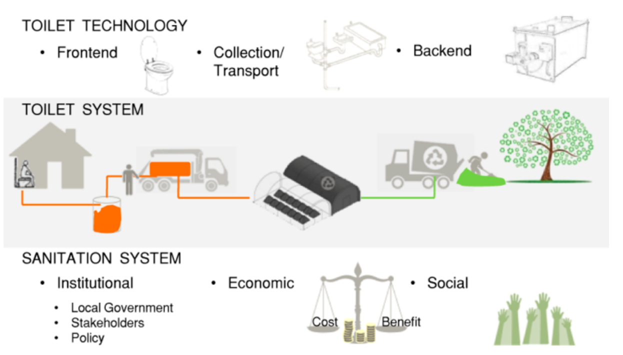

Figure 1. Illustration of the systems approach.

- Frontend: The frontend describes the pan or pedestal of the toilet that is usually employed for human defecation and urination.
- Collection/Transport: After defecation and/or urination the substrates have to be transported to the subsequent system components. In conventional systems the transport is through sewage pipes. In non-networked systems the transport takes place either on-site by means of built-in mechanical devices or off-site by transport via vehicles. Before or after transport the substrates have to be collected by bags, cartridges, chambers, containers, or other means.
- Backend: The backend encompasses the components and processes that take place after collection and transport. It includes the biological, chemical and/or physical treatment processes of the substrates generated in the frontend and for toilet systems also the final disposal or reuse/recycling.
- Other components: Even a conventional flush toilet with a septic tank may be made non-networked, if it uses water from rainwater harvesting. Similarly, toilets may use, for exmaple, electricity from solar collectors for pumps or control systems.

Classifications in the literature distinguish toilets by design type: *Dry toilets* do not need water for flushing the excreta. Instead, excreta may collected e.g. in a bag beneath the seat, sealed after each use. There are several subtypes: Commercial *composting toilets* support "managed" composting, where specific design features are met (controlling for oxygen, water, nutrients), as natural decomposition (self-built toilets) may not reach the temperatures necessary to destroy pathogens. For *dehydration toilets* feces are dried in the collecting chambers (e.g., ventilation mechanisms). UDDT (urine diversion dry/dehydration toilet) collects feces and urine separately, whereby for the feces different options exist, e.g. dehydration vaults. UDFT (urine diversion flush toilet) uses a water flush, but urine is collected separately from feces and two streams occur, urine ("yellow water") and feces plus flush water ("brown water"). *Solid–liquid separating toilets* collect solid and liquid together and use a mechanical separator. *Biogas toilets* are connected to a biogas reactor (bio digester), using waste as feedstock for anaerobic decomposition producing methane.

2.2. Study Design. For the present study, toilet technologies (systems) were classified as follows:

- Composting process based systems and dehydration toilets: Mainly dry toilets and UDDTs are using composting, but also some flush toilets and UDFTs.
- Anaerobic digestion based systems, such as biogas toilets: These are mainly flush toilets, but also a dry toilet and a UDDT could be identified.
- Other approaches: For other non-networked toilet systems, excreta are treated by chemical, combustion, membrane-based or mixed processes.

  The study focus was on commercial sanitation technologies and not on alternative toilets produced locally or by users themselves. For most of the surveyed toilets, the technology providers offered also operation and maintenance services.
- In the first step, a worldwide survey used Internet search, literature review and direct contacts with producers. It

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Table 1. Survey of Audited Toilet Technologies[a]

technology	type	dry = D/ flush = F	transport of feces	urine separation	additives	on-site treatment	sample size: effluent	sample size: sludge	sample size: compost	sample location
A	compost	D	mechanical	no	yes	special bacteria	1	0	0	South Korea (1 public toilet at producer)
B	compost	D	mechanical	no	no	dehydration	0	5	0	Namibia (ca. 1500 toilets)
C	compost	D	mechanical	no	no	dehydration	0	7	0	South Africa, Namibia (>10,000 toilets)
D	compost	D	gravity	in bowl	no	conventional composting	0	5	2	Namibia (ca. 2000 toilets)
E	anaerobic	D	gravity	no	no	conventional anaerobic	0	0	0	Madagascar (1 public toilet; 100 planned)
F	anaerobic	F	flush	no	yes	special bacteria	6	0	0	India (ca. 1000 toilets)
G	anaerobic	F	flush	no	yes	special bacteria	6	0	0	India (>10,000 toilets)
H	anaerobic	F	pour flush	in bowl	no	conventional anaerobic	2	2	0	India (2 prototypes in private homes)
I	other	F	flush	no	no	vermi-composting	1	0	0	South Africa (1 public toilet in use)
J	other	F	flush	no	yes	special bacteria	0	0	0	India (public and ca. 200 community toilets)
K	other	F	flush	separator	no	pretreatment	1	1	1	India (1 prototype in private home)
L	other	F	flush	chemical	yes	only partial treatment	2	0	0	China (9 public toilets)

[a]Comments: samples of compost are from central treatment; special bacteria = undisclosed bacteria about which producers made unverified claims about their performance.

Table 2. Selected Standards for Effluents and Sludge/Compost[a]

country	India, for water[13]	India, for land[13]	South Africa[14]	Germany, RAL[18]	EC, Eco Label[20]	U.S., NSF[22]	New Zealand[15]
parameters	effluent standards				sludge and compost standards		
fecal coliforms	<1000 MPN/100 mL				<1000 MPN/g	<200 MPN/g	NA
E. coli	NA		<1000 MPN per 100 mL				<200 MPN/g
pH	5.5–9	5.5–9	5.5–9.5			NA	
total suspended solids	<100 mg/L	<200 mg/L	<25 mg/L				
BOD_5	<30 mg/L	<100 mg/L	NA				
mercury (Hg)	<0.01 mg/L	<0.01 mg/L					
cadmium (Cd)	<2 mg/L	<2 mg/L					
chromium (Cr)	<2 mg/L	<2 mg/L					
lead (Pb)	<0.1 mg/L	<0.1 mg/L					
ammonia (as N)	<50 mg/L	<50 mg/L	<6 mg/L				
nitrogen (N)		NA		<300 mg/kg			
potassium (K)				<2000 mg/kg			
organic matter				>15%			

[a]Note: BOD_5 = biological oxygen demand (5 d at 20 °C); NA = no provision.

screened 45 commercially distributed technologies (list: Supporting Information SI-1). About 50% were composting process based, 30% anaerobic digestion based, and 20% used other approaches.

- In the next step, 12 toilet systems in use (Table 1) were selected for a qualitative evaluation to learn how they actually work with users in poor regions. Selection was determined by factors such as low costs for users, accessibility, willingness of the producer to cooperate, and other practical aspects. However, it was assured that four technologies were selected from each of the three groups, and that both Africa and Asia were represented.
- In subsequent field work, for each technology a few installations were visited. The producers arranged this and suggested the locations. An expert team visited the technology sites, collected grab-samples and let them analyze by local laboratories (preferentially accredited ones). However, not all producers allowed taking samples and in certain locations no laboratory could be found that was capable of measuring all parameters, in particular the microbiological ones.

About 95 criteria from the wider water sector were identified from a literature review (Supporting Information SI-2). Among core criteria are exposure to pathogens and vectors (human health), pollution (water, soil) and impact on biodiversity, criteria motivated from life cycle analysis (e.g., energy flows, material flows, land use), costs and related criteria (e.g., affordability), and criteria related to user acceptability (e.g., ambience quality, convenience of use, complexity of maintenance, cultural acceptance). The study focus was on the comparison of toilet technologies independently of the context of their implementation. (This context was noted, but not systematically studied.) Consequently, criteria were chosen as

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Table 3. Assessment of Effluents (Mean Values of Grab Samples for Different Toilet Technologies)[a]

parameters/technology	A	F	G	H	I	K	L
sample size	1	6	6	2	1	1	2
temperature in °C	NA	16	17	27	NA	15	NA
pH	8.3	7.4	7.4	7.4	7.4	8.5	9
total suspended solids in mg/L	18	166	149	1488	409	46	845
dissolved oxygen in mg/L	NA	7.4	5.9	4.0	NA	6.4	NA
COD in mg/L	1492	450	361	1950	749	288	9820
BOD_5 in mg/L	379	216	106	329	111	71	NA
ammonia (as N in mg/L)	30	217	101	147	22	<1.0	4705
total nitrogen (N in mg/L)	458	242	112	182	47	<1.0	6320
total phosphorus (P in mg/L)	77	8	11	63	25	4	230
total potassium (K in mg/L)	116	122	65	298	22	27	40050
mercury (Hg in mg/L)	NA	<0.01	<0.01	<0.01	<0.01	0.022	NA
cadmium (Cd in mg/L)		<0.02	<0.02	<0.02	<0.02	<0.02	
lead (Pb in mg/L)		0.22	<0.2	<0.2	<0.005	<0.2	
chromium (Cr in mg/L)		<0.05	<0.05	<0.05	<0.01	<0.05	
total bacterial count in CFU/ml	NA	1.0E6	2.4E6	1.7E4	NA	1.9E4	NA
fecal coliform MPN/100 mL	14	PR	1334	PR		ND	PR
E. coli in MPN/100 mL	5		1334				
fecal streptococci	NA	PR			PR	PR	NA
enterococci					NA		
salmonella		ND			NA	ND	

[a]Abbreviations: NA data not available; COD/BOD chemical/biological oxygen demand; microbiology: $a\mathrm{E}n = a\cdot 10^n$; PR present, ND not detected; CFU/MPN = test procedures.

follows: Costs were used for preselection. Health and environment was assessed by means of established parameters that could be tested by laboratories in developing countries. Further, user interviews were conducted to obtain information about the implementation context, user perceptions about toilet technologies and user preferences for certain key criteria with a clear meaning for users.

2.3. Materials and Methods. Preselection was based on a "*weak cost criterion*", that is, costs per use based on the sales price of the toilet, its estimated lifetime, the resulting renewal costs (after its lifetime, the toilet is replaced by a new one at the same costs), and on the number of users, using net present value (annualized costs).[9] Only technologies costing less than five cents per user/day according to the weak cost criterion were chosen for the audit.

Criteria for health and environment used parameters and established methods from WHO recommendations,[10] ISO guidelines (refs[11,12]), standards from India[13] and South Africa[14] for the discharge of wastewater into rivers or its application for irrigation, and standards (e.g., compost) from Australia and New Zealand (refs 15−17), Germany,[18] European Union (refs 19,20) and U.S. (refs 21−26). Table 2 summarizes the selected standards and Supporting Informaiton SI-7 provides additional information concerning the laboratory work. Notably, for the microbiological parameters two methods were used: CFU (count of cell-forming units) and MPN (most probable number test procedure to estimate CFU).

For user and expert surveys, the analytic hierarchy process (Supporting Information SI-4) was used as in the planning-oriented sustainability assessment framework to analyze preferences of the respondents and define, for each respondent, criteria weights from qualitative comparisons.[27] Confidence intervals used one-sided 95% *Clopper-Pearson* intervals; this method is conservative and suitable for small samples.[28]

3. TECHNOLOGY ASSESSMENT

3.1. Costs. Costs are critical for pro-poor technologies: If toilets are too costly relative to low income, poor people may practice open defecation. Therefore, in a sanitation system approach it is important to consider not only the toilet system, but also the economic feasibility for its implementation, which may depend on the business model.[9] (For instance, expensive technologies could be used for public and communal toilets with many users, as this use realizes an economy of scales typical for centralized systems.[29])

The audit confirmed that the sales price does not inform about the actual costs, as in a system perspective the actual costs are higher: For the toilet system one needs to consider running costs (e.g., additives, spare parts and professional servicing), and for the sanitation system there may be costs for transport (e.g., driving compost from feces to farms). Specifically, for system L (Supporting Information SI-3) the "weak cost criterion" explained only about a third of total costs, regardless of different hypotheses about the discount rate and time span for discounting.

However, companies generally do not disclose such information to the public; of 12 companies, only one provided information, but only confidentially. (With 95% significance one may expect that 78% of producers would not disclose all costs to the public.) Further, running costs may differ considerably between low-income and industrialized countries (refs 9,30,31 in a different context of decentralized wastewater treatment).

3.2. Health and Environment. Inadequate sanitation facilities may cause public health problems.[32] The assessment of health risks for users, the community at large and of the impact on the environment was based on the inspection of actually used toilet systems and grab samples. Effluents were tested for chemical and microbiological parameters listed in Table 3. Sludge/compost was tested for parameters listed in Table 4. The results indicated high variations for each

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Table 4. Assessment Compost and Sludge (Mean Values of Grab Samples for Different Technologies)[a]

						additional composting	
parameters/technology	B	C	D	H	K	D	K
sample size	5	7	5	2	1	2	1
moisture in % of mass	9	47	55	NA		13	NA
sand in % of mass	7	10	23			13	
organic matter (%)	73	71	57			66	
organic carbon (C in mg/kg)	NA			7270	2320	NA	1520
total nitrogen (N in mg/kg)	3660	3185	2500	1225	868	3050	1329
phosphorus (P in mg/kg)	2580	2643	2520	4795	556	3300	493
potassium (K in mg/kg)	2460	1771	920	950	685	1750	1762
total bacterial count, CFU/ml	NA			1.3E6	2.2E7	NA	2.8E6
total bacterial count, CFU/gram	4.0E7	6.5E8	5.4E8	NA		9.2E8	NA
fecal coli, MPN/gram	NA			PR		NA	PR
E. coli in MPN/gram	512	2160	1442			1250	
helminth, hookworm, larva, maggot, schistosome	NA			ND		NA	ND

[a]Abbreviations: NA data not available; *microbiology*: $a\mathrm{E}n = a{\cdot}10^n$; PR present, ND not detected; CFU/MPN = test procedures.

Table 5. Assessment of the technical issues about the functioning of toilets[a]

	criterion (possible problems)	relevance for	number of toilets	toilets with problems	confidence interval for problems	
1	impureness in toilet bowl (e.g., small or funnel like bowl)	dry toilets	4	2	10%	90%
2	cross contamination in toilet pan/bowl (no problem for tear-off edge)	urine diversion	2	0	0%	78%
3	functionality of flushing mechanism	flush toilets	7	not tested		
4	transport system problems (e.g., need to move waste with the hands)	not conventional	5	4	34%	99%
5	on-site soil contamination (e.g., infiltration in case of heavy use)	toilets with treatment system	11	8	44%	92%
6	treatment system problems (e.g., clogging)		11	7	35%	86%
7	maintenance efforts for front and back-end (e.g., regular efforts or even professional help needed)		12	9	47%	93%
8	performance of treatment process (e.g., undocumented or depending on parameters not controlled)		10	8	49%	96%
9	amount of sludge/feces produced or reduced (e.g., unsubstantiated claims)		11	5	20%	73%
10	accessibility of front and back-end (e.g., need to disassemble toilet for inspection)	all toilets	12	8	39%	88%
11	risks of additives (health of users, environment)		12	5	18%	68%
12	susceptibility to odor (compared to pour flush)		12	0	0%	22%
13	robustness and insect barrier		12	not tested		
14	any of the above-mentioned problems		12	12	78%	100%

[a]Comment: Summary of the detailed information from SI-6. In order to provide uniform information about the extent of problems despite different sample sizes, the confidence interval was computed; it is bounded by the lower/upper one-sided 95%-confidence limits for the percent of relevant toilets with the specified problems..

parameter. With respect to on-site treatment, all ten sampled systems (confidence limits: 74–100%) had low quality of either effluents or compost/sludge.

- Microbiological quality of byproducts (*E. coli*: health risks for the community at large) failed the respective standards for four of five technologies (34–99%); two effluent data were compared to South African standards, 3 sludge/compost data to New Zealand standards.
- Effluents were unfit for discharge into water bodies. For BOD_5, six of six technologies (61–100%) failed Indian standards and for ammonia and for suspended solids six of seven technologies (48–99%) failed South African standards. Another concern was lead in water.
- Total nitrogen in compost/sludge was above a German standard for five of five technologies (55–100%), even after additional composting (two of two technologies, 22–100%).

3.3. Other Issues. Users of the visited systems were asked about their perceptions and representatives of institutional stakeholders informed about the organization of local sanitation (e.g., sludge collection). The interviews did not aim at systematic assessments of social, cultural and institutional issues. Rather, the feedback was the basis for additional qualitative technical assessments by experts, using the criteria of Table 5: It displayed lacking maturity of all systems (confidence limits: 78–100% for failure).

3.4. Overall Assessment. Two surveys were conducted to determine the relative importance of the criteria for users and experts. A survey among eight experts of TÜV (a German-based technology certification body) resulted in the following average criteria weights: 30% for health, 20% for environment (pollution), 19% for economic issues (costs and benefits), 16% for socio-cultural issues (acceptance), and 14% for technology issues (functioning); they also assessed the importance of the technical criteria (Supporting Information SI-6). A similar survey was conducted among potential users from a slum in Raisen, a rural town in Madhya Pradesh, India: Again health and pollution were most important (Supporting Information

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SI-4 and SI-5). Costs were not so important for users, as they expected the (municipal) government to pay most for the sanitation improvements. Thus, both groups considered health and pollution as the most important issues.

Summarizing by these importance levels, the following weaknesses were identified for the surveyed commercial toilet technologies:

- Health and hygiene (users, community at large): Aside from unknown risks by undocumented additives, there were concerns about the contamination of sludge and effluents with pathogens. With respect to cleanness, there were problems with mechanical transport mechanisms (#4/Table 5). Judging from the field visits, training of users before use was generally advisible.
- Environment: The discharge of the effluents into water bodies or the application of sludge in agriculture was problematic for all tested technologies. There were also concerns about undocumented additives and sewage overflows/leakages (#5/Table 5).
- Costs: Actual and sales costs may differ considerably, whence lacking cost-transparency may make the selection of innovative toilet technologies problematic for utility providers and organizations with an interest in supporting pro-poor sanitation solutions in developing countries.
- Other: Most users were satisfied with their toilets, especially where the frontend resembled "normal" pour flush toilets; odor was not perceived as a problem. However, compared to conventional toilets, most technologies needed considerable maintenance efforts (#7/Table 5). Thereby, toilets provided by international donor NGOs often depended on imported (and therefore expensive) spare parts from industrialized countries.

4. POLICY IMPLICATIONS

4.1. Barriers to Innovation. Different organizations and research groups apply different assessment concepts. For, sustainability is a multipronged objective encompassing, for example, aspects of health and hygiene, impact on the environment, social, economic and cultural issues, or policy and governance issues.[33] There is an abundance of assessment methods with, for example, at least 54 approaches for sustainability assessment based on system analytic approaches.[34] Therefore, different organization may deem different technologies as best. A well-documented example is the *Roediger NoMix* toilet. Its concept was well-received by researchers (refs[35−39]), but a quality check[12] for production failed and production was stopped (refs[40,41]).

Another barrier may be prejudice by users and political decision makers, who may consider non-networked toilets as inferior to conventional ones. For in developing countries, often toilets are directly purchased by the government and then provided to the villages (e.g., community toilets); some toilets were manufactured and installed by NGOs. Thereby, unclear responsibilities or multiple government agencies in charge of toilet provision, some with prejudices against certain toilet types (e.g., dry toilets) may cause institutional barriers, as may lacking regulations regarding e.g. application of treated human excreta in agriculture (urine separation or composting toilets).

4.2. Standardization of Toilet Technologies. Discussions with producers of innovative toilet technologies have shown that they, too, consider such barriers as a problem. As a possible solution, producers would be interested in an internationally recognized certification procedure, based on established standards. A standard is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose. There is no general standard for non-networked sanitation solutions (Section 2.3: standards only for certain composting toilets). Further, current national standards miss important aspects (e.g., risks from parasites).

- For producers, certification would be a competitive advantage. It would confirm that their products are technically mature, safe and compliant with environmental regulations. This reduces their liability risk.
- There are also advantages for the wider sanitation sector, as common terminology from standards would facilitate communication and evaluation, leading to higher market efficiency (lower transaction costs by easier access to information). The resulting faster dissemination of innovations may also attract investments: Standards contribute to economic growth.[42]
- Further, product certification is relevant for consumers, guaranteeing them minimum safety, and for organizations interested in the development and promotion of non-networked sanitation technologies. The audit procedure for technology certification would define a common basis for assessments. This would reduce information costs (currently, for each project the criteria are defined anew) and help to identify true innovations.

However, product certification should not discourage the development of new technologies for the poor. A certificate should therefore focus on certain basic requirements, which producers of innovative toilet technologies can fulfill with reasonable additional efforts for product development, while keeping the toilet costs low. The criteria of Table 5 define certain minimal requirements:

- Toilets should be easy to use and aesthetically appealing. This entails that they need no specific procedures for use (e.g., change of seating position), that also children can use them safely after a short instruction, that they are compatible with existing habits (e.g., use of hard or soft cleaning material), that daily cleaning does not require special skills, that there should be no offending smell (i.e., there is a flush, a ventilation or additives are used), that feces should not be visible under the toilet seat, and that the toilet bowl should not be susceptible to impureness (a problem with mechanical devices transporting feces out of sight).
- Toilets should perform, as promised by their producers. This entails a low susceptibility to contamination of urine in the bowl or pan (for urine separation toilets), the functionality (meaning also a low susceptibility to failure) of the flushing mechanism or of the built-in mechanical transport mechanism (dry toilet), and of the mechanical or biological features of the treatment system, if there is one. For the method of treatment it should be well-documented that it removes pathogens from waste streams.
- In particular, toilets should be safe for health and the environment. This entails that neither users, nor operators (service personnel) should be exposed to

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hygienic risks, that additives (e.g., for disinfection) are proven to be safe, and that reusable substrates are safe in case of recycling. Further, users should not come into contact with hazardous disposables and operators should be able to protect themselves. Further the systems should be tight to avoid infiltration into the ground and toilets should not cause insect problems.
- Toilets and their treatment systems should be easily accessible for inspection and maintenance and for users, there should be no excessive efforts with respect to regular maintenance activities (e.g., flattening of feces or shifting waste, adding bacteria or caring for worms) and also no special knowledge-needs (e.g., simple user manuals).
- Further, the robustness (strength) of whole front-end system should be assured. This means the measurement of the robustness of materials against loads and pressures compared to standards.

As to the development of standards, following the definition of criteria and testing procedures, one needs to identify the relevant stakeholders (manufacturers, government authorities, representatives of standardization bodies) in the relevant market (developing countries). Their feedback about the criteria and the relative importance of these criteria is needed for revisions of the standard, to make it practical and acceptable. Finally, the (revised) standard needs the approval of a body that accepts ownership of the standard and has the capacity to disseminate it (e.g., training of certification experts). For the implementation, in an initial stage such a standard would be part of a private system of accreditation and certification: The standard owner entrusts an administration body, which entrusts an accreditation body that in turn accredits certification bodies for inspections of producers requesting certificates for their toilets. Later, such a standard may be used by governments to define national standards and in the final stage it may become an ISO standard.

4.3. Conclusion. Non-networked toilet technologies are a promising approach for the poor in developing countries, where local business would be prepared to support the implementation of on-site technologies at least for urban regions, but in general not of networked technologies (ref[43] for Sub-Saharan Africa). However, an audit of a sample of different types of commercially available non-networked toilet technologies revealed serious concerns: All toilets had technical problems, in particular regarding their treatment system (e.g., excessive maintenance needs), which was also confirmed by insufficiently treated effluents and sludge. This problem was aggravated by lacking cost transparency; running costs may become unaffordable for poor users. Standardization could resolve this problem from the technology side and guarantee that the toilets will be safe for health and for the environment. These criteria were the key concerns for the inquired experts and consumers.

However, also technologies which satisfy (future) standards for product certification may become problematic, when improperly implemented.[8] (Here the context is the larger sanitation system.) Thus, application of compost in agriculture could cause hygienic risks even after additional composting (systems D and K; Table 4). Conversely, if the sludge/compost from a toilet is cocomposted with organic wastes (e.g., vegetable wastes from local markets, corn or banana stalks from farmers), then skilled operators (e.g., communal composting sites) could ensure the production of high quality compost (refs[44−46]), making also low-quality compost/sludge from toilets overall beneficial. Therefore, subsequently to the development of technology standards there remain research needs to identify sanitation system specifications that maximize the benefits from using certified toilet technologies.

■ ASSOCIATED CONTENT

Supporting Information

It lists initially reviewed technologies, initially considered criteria, outcomes of user and expert surveys about the importance of criteria, qualitative technical assessments of technologies, a cost assessment of one technology, and detailed information about methodology. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b00887.

■ AUTHOR INFORMATION

Corresponding Author

*Phone +43-1-476545057; fax: 43-1-47654-5092; e-mail: markus.starkl@boku.ac.at.

Notes

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