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Decision Support for Redesigning Wastewater Treatment Technologies

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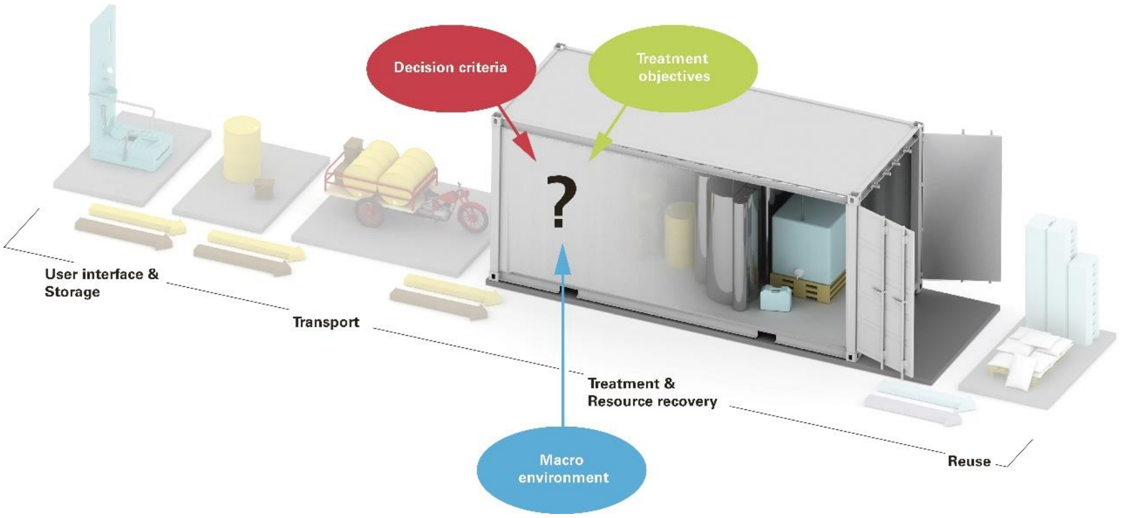


TOC/Abstract art

ABSTRACT

This paper offers a methodology for structuring the design space for innovative process-engineering technology development. The methodology is exemplified in the evaluation of a wide variety of treatment technologies for source-separated domestic wastewater within the scope of the Reinvent the Toilet Challenge. It offers a methodology for narrowing down the decision-making field based on a strict interpretation of treatment objectives for undiluted urine and dry feces and macro-environmental factors (STEEPLED analysis) which influence decision criteria. Such an evaluation identifies promising paths for technology development such as focusing on space-saving processes or the need for more innovation in low-cost, energy-efficient urine treatment methods. Critical macro-environmental factors, such as housing density, transportation infrastructure, and climate conditions were found to affect technology decisions regarding reactor volume, weight of outputs, energy consumption, atmospheric emissions, investment cost and net revenue. The analysis also identified a number of qualitative factors that should be carefully weighed when pursuing technology development; such as availability of O&M resources, health and safety goals, and other ethical issues. Use of this methodology allows for co-evolution of innovative technology within context constraints, however for full-scale technology choices in the field, only very mature technologies can be evaluated.

INTRODUCTION

Globally we are facing a major sanitation crisis. This crisis is not only about providing proper sanitation facilities to the 2.5 billion people who lack access to the health benefits and personal dignity which these systems provide[1]. It is also about doing so in a way that creates synergies to help solve the global environmental crisis, especially with respect to water pollution and (economic) resource scarcity. A shift from conventional wastewater treatment with little reuse has already started with many experts calling for greater focus on resource efficiency and alternative solutions to the prevailing paradigm of sewer-based centralized wastewater treatment[2,3]. Different international organizations are taking up these ideas and implementing them in their development strategies. The Bill & Melinda Gates Foundation, for instance, is responding to this double crisis through the Reinvent the Toilet Challenge (RTTC), which aims to foster innovation for low-cost toilets that sanitize human excreta and recover valuable resources without a sewer connection or harmful discharge. Ultimately these alternative solutions can have far reaching consequences for public health and the protection of sensitive environments.

A prerequisite for developing innovative solutions is expanding the design space beyond what is conventionally considered the wastewater system. Separate collection and treatment of different waste flows (e.g. urine, feces, water) has proven advantageous for improving treatment capacity in existing treatment plants[4], for resource efficiency[5], and for contributing to food security[6]. There is ample evidence that resource recovery is easier from concentrated homogenous waste than from mixed, diluted solutions like wastewater (e.g. energy from feces, fertilizer from urine).

While this thinking can provide inspiration to new process engineering innovation, there is also need to understand how new technologies will function in the macro-environmental context in which they are placed. Contextual factors such as predominant culture, economy, institutional control, climate and infrastructure will affect public acceptance and technical feasibility of innovations[7,8]. Studies of technology development have shown that such macro-environmental factors heavily influence the success of innovations[9,10]. Indeed, technology development is increasingly recognized as a process of co-evolution within existing socio-technical regimes[11,12]. The challenge for technology developers is to account for these external factors within the design process. There is a growing need for decision support tools to identify critical engineering and context parameters that can guide design and decision-making within this complex design space, particularly during early stages of technology development.

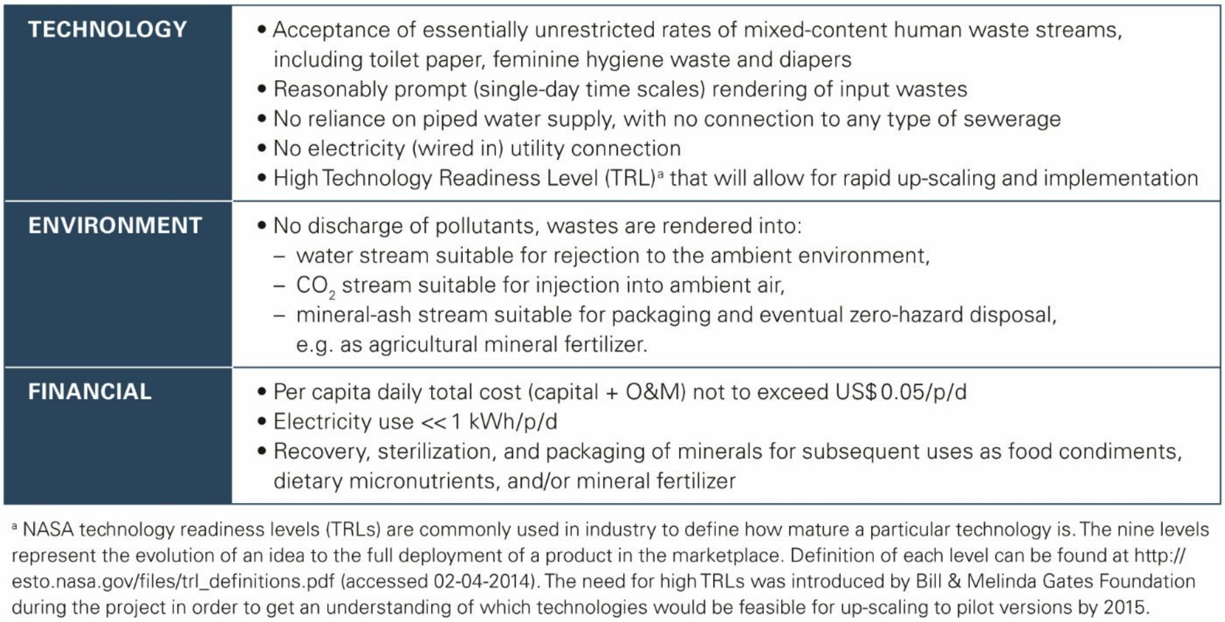
The objective of this paper is to present a methodology for structuring the design space for innovative process engineering technology development, as well as for urban planners and consulting engineers. The method combines process engineering objectives based on source separation with an analysis of site-specific macro-environmental factors in a detailed evaluation of potential treatment technologies. Using this analysis process engineers can identify critical macro-environmental factors that influence design criteria and narrow the design space to a workable number of options.

METHODOLOGY

The methodology applied in this paper is derived from a comprehensive decision analysis framework developed for the selection of urine-treatment technologies in different scenarios[7]. In the present paper it is expanded to include treatment of feces and the macro-environmental criteria are adapted to fit a low-income country context. The methodology begins by listing design requirements and translating them into process engineering objectives and decision criteria (Step 1). The process engineering objectives are considered obligatory while the critical decision criteria are desired attributes that can be adjusted based on local conditions. The process engineering objectives are used to screen suitable (combinations of) treatment technologies (Step 2). Then, a macro-environmental content analysis is performed to assess how external factors may affect technology choice (Step 3). Suitable technologies are then evaluated based on decision criteria and critical macro-environmental factors (Step 4). Finally, the (combinations of) technologies are ranked based on the results of the previous steps and the preference of local stakeholders (Step 5). It should be emphasized that this procedure is generally iterative. The final step requires technologies that are ready for piloting in a specific local setting. Since Phase 1 of the RTTC focused on development of prototypes this final step is outside the scope of the paper. Instead, it shows how this methodology can be used to evaluate different technology approaches.

To illustrate the use of the methodology, we apply it to the case of excreta treatment technologies that meet the requirements as laid out by the Bill & Melinda Gates Foundation in the RTTC call (Table 1). The visionary call stated that, "Ideally, [RTTC] will yield a facility that is suitable for a single-family residence in the developing world; takes in the bodily waste of an entire family; and outputs useful waste-fractions immediately and safely in usable forms. This would be accomplished without reliance on piped-in water, with no connection to any type of sewerage and with no electric utility connection." Experts at Eawag, the Swiss Federal Institute of Aquatic Science and Technology, did not consider complete on-site treatment of excreta feasible at an affordable cost in the near future and thus proposed a toilet connected to a transportation system and locally-based treatment plant. In 2011, Eawag, in cooperation with the Austrian design company EOOS, received RTTC funding to develop a proof of concept for a source-separating toilet with resource recovery from undiluted urine and dry feces at a nearby Resource Recovery Plant (RRP). The important new features of the toilet are the availability of water for flushing, hand washing and anal hygiene (treated and recycled on-site using membrane technology), a hygienic collection system, and an innovative toilet design (www.bluediversiontoilet.com)[13]. The methodology presented in this paper was developed to determine the optimum urine and feces treatment technologies to be used at the RRP.

Table 1: Breakdown of the design requirements in the RTTC based on specific categories (based on guidelines from the Bill & Melinda Gates Foundation[14,15]).



TECHNOLOGY	• Acceptance of essentially unrestricted rates of mixed-content human waste streams, including toilet paper, feminine hygiene waste and diapers • Reasonably prompt (single-day time scales) rendering of input wastes • No reliance on piped water supply, with no connection to any type of sewerage • No electricity (wired in) utility connection • High Technology Readiness Level (TRL)[a] that will allow for rapid up-scaling and implementation
ENVIRONMENT	• No discharge of pollutants, wastes are rendered into: – water stream suitable for rejection to the ambient environment, – CO_2 stream suitable for injection into ambient air, – mineral-ash stream suitable for packaging and eventual zero-hazard disposal, e.g. as agricultural mineral fertilizer.
FINANCIAL	• Per capita daily total cost (capital + O&M) not to exceed US$ 0.05/p/d • Electricity use << 1 kWh/p/d • Recovery, sterilization, and packaging of minerals for subsequent uses as food condiments, dietary micronutrients, and/or mineral fertilizer

[a] NASA technology readiness levels (TRLs) are commonly used in industry to define how mature a particular technology is. The nine levels represent the evolution of an idea to the full deployment of a product in the marketplace. Definition of each level can be found at http://esto.nasa.gov/files/trl_definitions.pdf (accessed 02-04-2014). The need for high TRLs was introduced by Bill & Melinda Gates Foundation during the project in order to get an understanding of which technologies would be feasible for up-scaling to pilot versions by 2015.

RESULTS

Step 1: Process engineering objectives

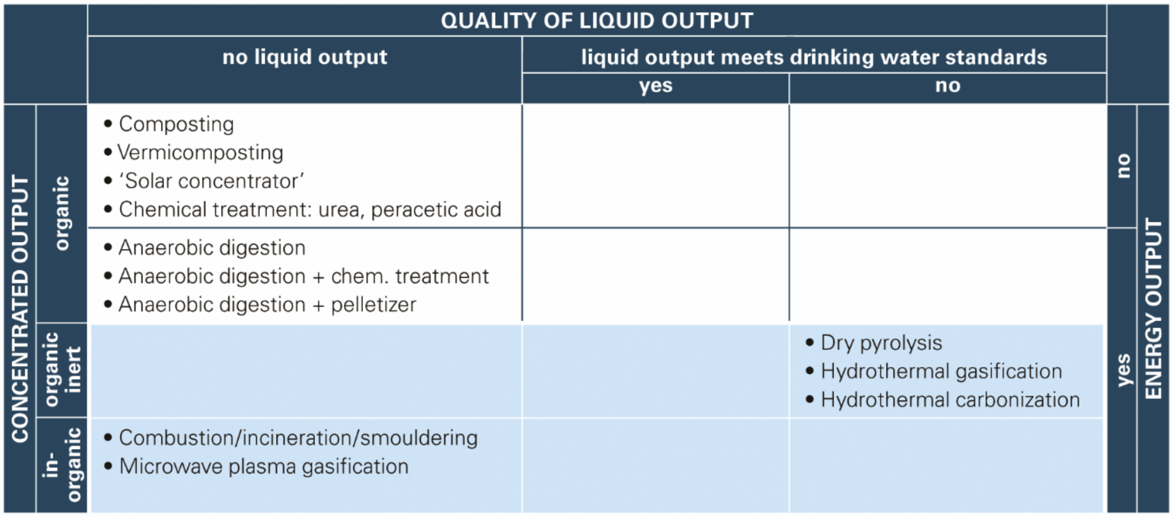
As shown in Table 1, the RTTC design requirements clearly limit the design space both in the type of technology and process engineering objectives. The requirements related to treatment technology essentially require that treatment processes must be reasonably fast and independent of existing infrastructure. The call also specifies strict discharge requirements regarding the release of pollutants to the environment. In order to translate the rather vague requirements on the quality of liquid and solid outputs into rigorous process engineering objectives, we consulted the Bill & Melinda Gates Foundation for clarifications. We arrived at the consensus that final liquid outputs must meet drinking water quality standards (as defined by the US Safe Drinking Water Act with zero pathogens) and solid outputs must occur in stabilized form (either as inert organic matter or inorganic salts). Although the list of desired design features for the RTTC call contains additional points related to user convenience and comfort, these are not relevant for the choice of treatment technology; rather they were included in the design of the toilet itself.

Step 2: Identification and characterization of technologies

Based on the process engineering objectives identified in Step 1, decision matrices were developed for treatment technologies for separated feces (Table 2) and urine (Table 3). Available treatment technologies were identified through a detailed literature review[16–18] and communication with other research institutions participating in the RTTC. The different treatment technologies were then categorized in decision matrices according to how they fulfilled the different quality requirements for the liquid and concentrated residuals. Possible energy output was also included for treatment of feces since this will affect decision criteria related to costs and energy consumption. This method of characterization allows for an initial screening of the technologies to see which fulfill the objectives. Technologies included in the screening is based on literature[18] and the range of technologies proposed in the RTTC program. Technologies that fall within the shaded areas in Tables 2-3 meet the RTTC requirements. Note that cost criterion are ignored since the low technology readiness level (TRL) of many technologies does not allow for reliable cost estimates. Technologies passing this initial screening will be further evaluated based on critical decision criteria (Step 3).

Only five dry feces treatment options produce inert organic or inorganic concentrated outputs and therefore fulfill RTTC requirements (Table 2). Since all of these technologies are relatively new, anaerobic digestion was also carried forward into Step 3 for comparison because of its high TRL. This resulted in six options (Table 4) for further evaluation in combination with urine treatment technologies. Please note that we do not exclude any feces treatment technology based on quality of the liquid output. Since we only evaluate processes that can be combined to provide treatment of a liquid (urine) and a solid (feces) stream, we add this liquid to urine for further treatment.

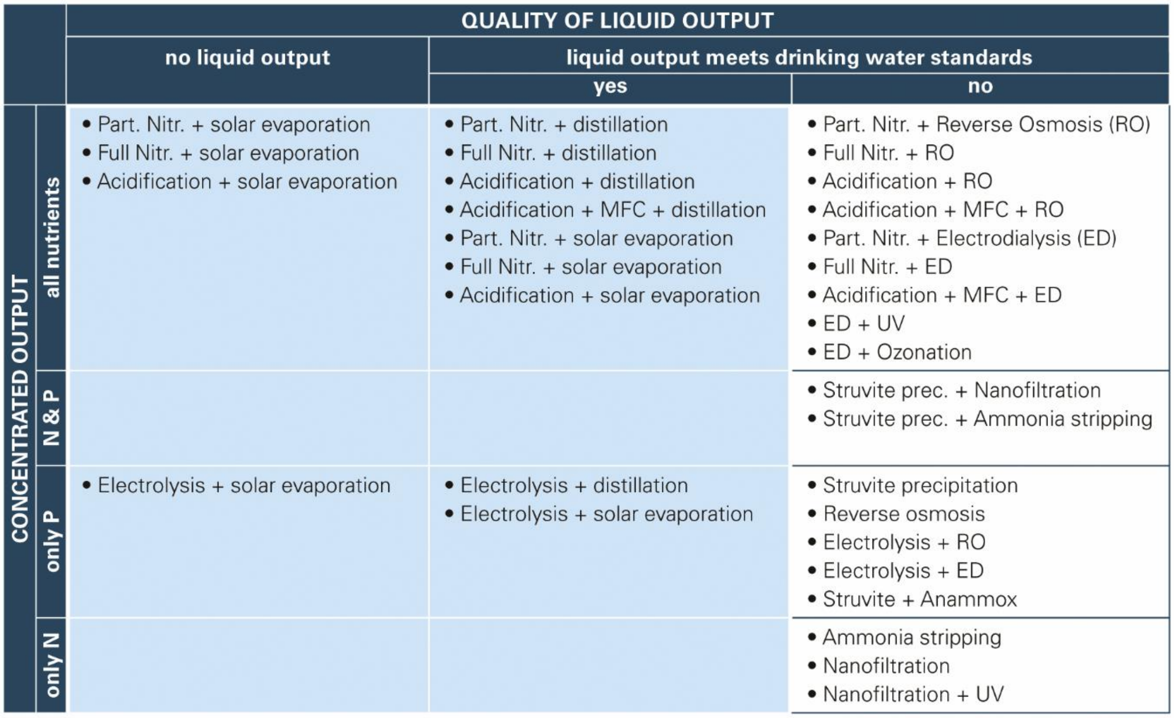
Table 2: Classification of dry feces treatment options. Note that this classification does not account for thickening processes meaning that slurry outputs are classified as “no liquid output”. Screening is based on theoretical treatment performance.



		QUALITY OF LIQUID OUTPUT				
		no liquid output	liquid output meets drinking water standards			
			yes	no		
CONCENTRATED OUTPUT	organic	• Composting • Vermicomposting • 'Solar concentrator' • Chemical treatment: urea, peracetic acid			no	ENERGY OUTPUT
		• Anaerobic digestion • Anaerobic digestion + chem. treatment • Anaerobic digestion + pelletizer			yes	
	organic inert			• Dry pyrolysis • Hydrothermal gasification • Hydrothermal carbonization		
	in-organic	• Combustion/incineration/smouldering • Microwave plasma gasification				

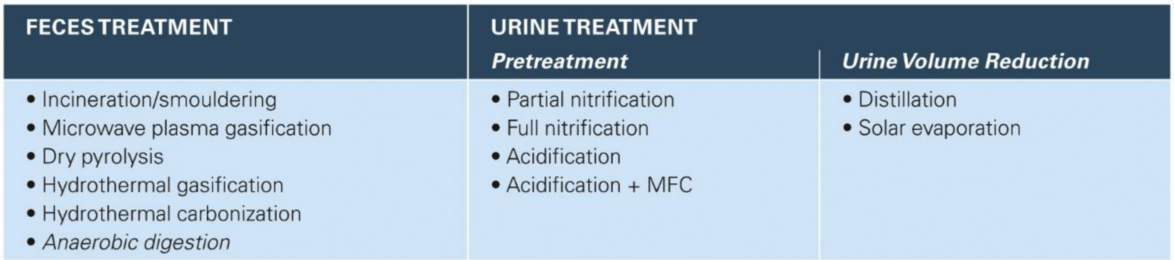
Most of the urine treatment technologies listed in Table 3 are already a combination of two technologies, mainly to stabilize the urine and concentrate the nutrients (for more information, see SI). Stabilization prevents nitrogen loss by ammonia volatilization and the hazardous release of reactive nitrogen into the environment. Many options recover nutrients but do not ensure that the remaining liquid meets drinking water quality standards. Therefore, they are not further evaluated. The only options which fulfill the requirements are combinations of solar evaporation (with or without water recovery) and vacuum distillation (referred to as distillation), both combined with a pretreatment step to stabilize the urine. Solar evaporation and distillation can recover similar amounts of nutrients.

Table 3: Classification of urine treatment technology options where 'all nutrients' does not relate to 100% recovery, but means that a considerable amount of each nutrient is recovered. Abbreviations: Part=partial, Nitr.=Nitrification, MFC=Microbial fuel cell, Prec. =precipitation, RO=Reverse osmosis, ED=Electrodialysis, UV=UV light treatment for sanitization. Screening is based on theoretical treatment performance.



		QUALITY OF LIQUID OUTPUT		
		no liquid output	**liquid output meets drinking water standards**	
			yes	**no**
CONCENTRATED OUTPUT	**all nutrients**	• Part. Nitr. + solar evaporation • Full Nitr. + solar evaporation • Acidification + solar evaporation	• Part. Nitr. + distillation • Full Nitr. + distillation • Acidification + distillation • Acidification + MFC + distillation • Part. Nitr. + solar evaporation • Full Nitr. + solar evaporation • Acidification + solar evaporation	• Part. Nitr. + Reverse Osmosis (RO) • Full Nitr. + RO • Acidification + RO • Acidification + MFC + RO • Part. Nitr. + Electrodialysis (ED) • Full Nitr. + ED • Acidification + MFC + ED • ED + UV • ED + Ozonation
	N & P			• Struvite prec. + Nanofiltration • Struvite prec. + Ammonia stripping
	only P	• Electrolysis + solar evaporation	• Electrolysis + distillation • Electrolysis + solar evaporation	• Struvite precipitation • Reverse osmosis • Electrolysis + RO • Electrolysis + ED • Struvite + Anammox
	only N			• Ammonia stripping • Nanofiltration • Nanofiltration + UV

Table 4: Overview of the possible urine and feces treatment technologies meeting the strict treatment objectives set by the RTTC. Note that anaerobic digestion is included for comparison purposes although it does not fulfill the requirements. Cost criterion are ignored since the low TRL of many technologies does not allow for reliable cost estimates.



FECES TREATMENT	**URINE TREATMENT**	
	Pretreatment	***Urine Volume Reduction***
• Incineration/smouldering • Microwave plasma gasification • Dry pyrolysis • Hydrothermal gasification • Hydrothermal carbonization • *Anaerobic digestion*	• Partial nitrification • Full nitrification • Acidification • Acidification + MFC	• Distillation • Solar evaporation

Step 3: Context analysis (STEEPLED)

Evaluation of technology combinations in this paper has so far been done independent of context. In order to access how particular macro-environmental context factors may affect the treatment processes at an RRP, a STEEPLED analysis was conducted. STEEPLED is a framework for describing external macro-environmental factors commonly used in market research or strategic analysis (originally known as PEST analysis[19]). It covers Social, Technological, Economic, Environmental, Political, Legal, Ethical and Demographic factors that can influence the design of the treatment processes, costs and end-product outputs of the proposed RRP (Table 5). Note that certain factors can be classified under several categories, e.g. global climate change can be seen as both an environmental and an ethical issue. The list is derived from Larsen et al.[7] and updated based on the combined experiences of the authors.

The Bill & Melinda Gates Foundation already set a number of boundary conditions (Table 1), which would normally be identified during a STEEPLED analysis. For instance, the RTTC call requires new technologies to be independent of water, electrical and wastewater infrastructure. Similarly, the requirement for no emissions of liquid pollutants mean that we can assume that regulations for protection of the local aquatic environment will be met as they are to a large degree already incorporated in the process engineering objectives. However, the call does not contain specifications for atmospheric outputs which are important for environmental and ethical reasons and are thus included in Table 5. Furthermore, it was judged that none of the potential demographic factors would greatly affect technology performance. Rather, changes in these factors would affect the number of treatment plants needed and frequency of emptying. Such factors must be more closely assessed on a case-by-case basis for local business models which would require a separate STEEPLED analysis.

The remaining factors from Table 5 were carefully analyzed with regards to their influence on process engineering and the strength of the potential impact. Some of them are deemed to have a weak or minimal impact on selection of technical options. A good example is the incidence of diarrhea, which intuitively is judged much more influential than is suggested by feces volume calculations from literature[20,21]. Whereas a 1% increase in diarrhea incidence is dramatic from the point of view of health, it will not have any measurable impact on the dry matter content of feces. Dietary preferences will affect the influx of nutrients[22] to the proposed RRP, but it is judged that variation within a specific population will not be great[23], and hence will mostly impact on fine adjusting treatment techniques to the local context.

There are also a number of factors with qualitative characteristics that may strongly influence the establishment of a new technology. The availability of O&M resources, both human and material, can affect the complexity of technology that can be expected to be maintained. Since operational failure is a significant threat to the sustainability of sanitation systems[24] this impact is important to consider. Public perception, political support (or lack of it) and local corruption levels can also have significant influence on the success of technology development[10]. In addition, there are a number of ethical factors that will need to be considered, particularly with regard to trade-offs between profit margins and community/environmental responsibility. For example, from the perspective of poor local farmers, it may be preferable to recover organic material along with the nutrients in order to provide a complete soil conditioner. However, inorganic nutrient recovery may be more profitable. This is of course also linked to matching output products with local fertilizer preferences, fertilizer availability, and soil conditions if the aim is to support local agriculture and businesses. In addition, fertilizer regulations and precautionary principles regarding reuse may translate into demands for additional treatment, thus also affecting the output quality and costs. However, it is difficult to quantify the specific impact that these factors will have on decision criteria or technological design. These qualitative factors are thus not included in the subsequent analysis, but they will belong to the list of criteria when actual technology is chosen in a specific scenario (Step 5).

In order to illustrate how this methodology could be used in technology evaluation, the rest of this paper focuses on quantifiable factors (marked with checks in Table 5). These factors are generally technological, economic, and environmental issues that affect the importance of one or more of the following quantifiable decision criteria: reactor volume, weight of outputs, energy demand, atmospheric emissions and costs. These factors are taken into account in Step 4.

Table 5: External macro-economic factors (STEEPLED) influencing the selection of technology combinations for the RRP.

STEEPLED Factor	Explaining remarks	Influence on the importance of decision criteria	Quanti-fiable
Social			
Anal hygiene practice	Amounts of wiping material	Reactor volume	✓
Consumption patterns	Amount of nutrients in excreta	Local process adjustment	
Incidence of diarrhea	Diarrhea leads to slightly greater dilution & volumes	Local process adjustment	
Local fertilizer preferences	Influences form and acceptance of output	Quality of output	
Public perception	Technology must be viewed positively if it is to be used properly	—	
Technological			
Existing infrastructure	RTTC call requires independence from existing infrastructure	—	
Housing density	Influences the availability of land for RRP	Reactor volume	✓
Transport infrastructure	Large volumes increase costs	Weight of output	✓
Economic			
Availability of credit & financing	Affects potential to establish new business	Investment costs	✓
Availability of fertilizers & fertilizer subsidies	Affects revenue potential	Net revenue	
Availability of O&M resources	Affects operational costs and feasibility	Operational costs & robustness of technology	
Per capita income of population	Affordability of technology	Investment & operation costs	✓
Proximity of output end-users	Affects transport costs for delivery of products	Weight of output	✓
Environmental			
Availability of alternative energy sources	RTTC call specifies independence from electrical grid	Energy demand	✓
Climate conditions	Affects biological processes, energy sources and outputs, e.g. products may have less stability	Quality of outputs, energy demand, & robustness of technology	✓
Local agricultural conditions & topography	Degraded soils drives recovery of carbon & nutrients	Quality of output	
Protection of local environment	RTTC requires zero liquid output, but atmospheric outputs may be problematic	Type of atmospheric emissions	✓
Protection of global environment	Emissions to the atmosphere are relevant	Type of atmospheric emissions	✓
Political			
Corruption levels	E.g. granting of contracts to those with political connections, or potential conflicts with existing service providers	—	
Political support	Potential bias for capital intensive infrastructure, but availability of subsidies may lower the importance of costs	Costs	
Legal			
Fertilizer regulations	Additional treatment, e.g. micro-pollutants removal	Quality of outputs & costs	
Pollution control laws	RTTC call only limits liquid output, not atmospheric outputs	Type of atmospheric emissions	✓
Ethical			
Health & environment	RTTC call only limits liquid output, not atmospheric outputs	Type of atmospheric emissions	
Responsibility for the poor	Preference for complete fertilizers for local farmers	Quality of output	
Precautionary principle regarding reuse	Additional treatment, e.g. micro-pollutants removal	Quality of output & costs	
Demographic			
Population growth	Potential adaptability for changing treatment loading	—	
Working hours	Amount of input material collected from homes	—	

Step 4: Evaluation of technologies based on context parameters and decision criteria

Based on the RTTC design requirements (Table 1) and STEEPLED analysis (Table 5) a number of decision criteria can be identified for evaluating technologies. Not surprisingly, costs are major criteria for selecting technologies for the urban poor. For evaluation purposes we compare investment costs and net revenue. Whereas the RTTC design requirements only state the total costs, some of the STEEPLED criteria indicate that it may be of value to distinguish between investment costs and running costs. For lack of better information, we assume that labor and maintenance costs are proportional to the investment costs, and thus include only consumables in the running costs. Since valuable products are generated, we subtract the running costs from the market value of these products in order to obtain the net revenue.

The RTTC criteria state independence of an electrical grid, but make no statements with respect to energy consumption from other sources. Apart from the financial costs of such solutions (included in the investment and/or running costs), the STEEPLED analysis show that environmental factors will influence the viability of solutions based on local energy sources, e.g. solar energy. Truly energy-independent solutions will rely only on the energy available in the excreta. For comparison, we show technology combinations optimized for energy efficiency (Figure 1c).

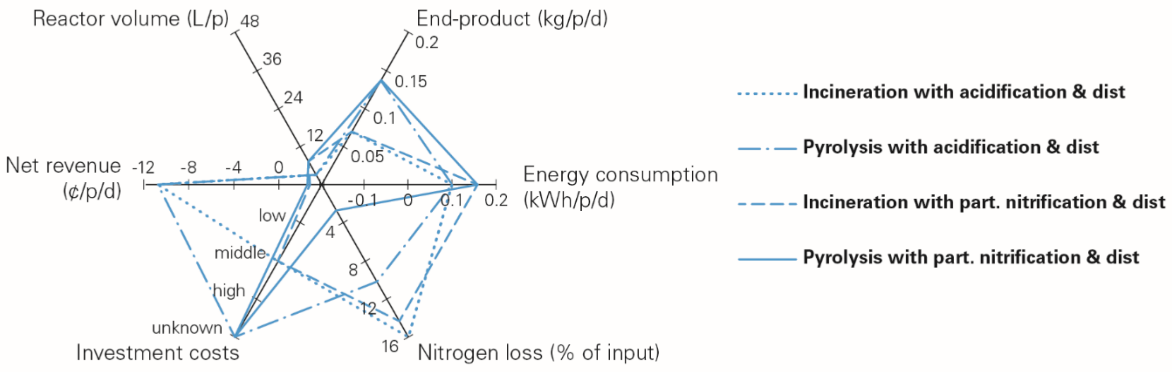
The RTTC criteria on output quality from feces treatment consider only stability and not volume or weight. Although these are interdependent (stabilization of feces mostly also involve weight reduction), the STEEPLED analysis is more explicit with respect to the different external factors determining the importance of weight reduction. Distance from production to use and soil quality are the most important factors influencing the importance of these criteria. It should be noted that in some scenarios, the RTTC requirement of mineral ash output may not be justified due to STEEPLED factors such as, responsibility for the poor and local agricultural conditions (e.g. an area with degraded soils and low-income farmers may need organic-rich soil conditioners such as stabilized fecal solids).

From the STEEPLED analysis, reactor volume is an important criterion that is closely related to housing density and local hygiene practices. Furthermore, a number of macro-environmental factors point to the need to consider atmospheric emissions and environmental pollution. In the RTTC call, there are no explicit limitations on the emissions to the atmosphere, but especially emissions of reactive nitrogen compounds would be highly critical[25]. The net loss of nitrogen can be used as a proxy for atmospheric emissions.

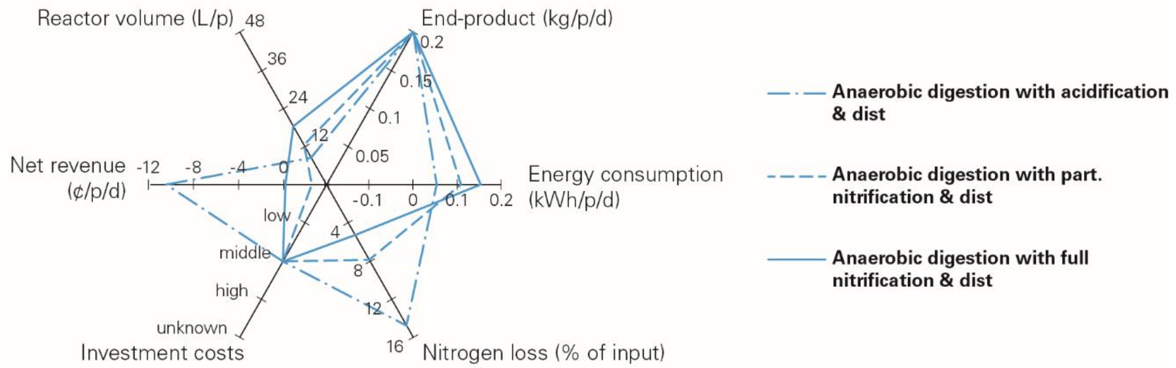
Finally, the modified RTTC call defined TRL as a factor. TRL is of course of high importance for the choice of technology within a defined time frame, but is not in itself a criterion for the suitability of a technology. We thus refrain from including TRL as a decision criterion, but make a separate comparison of the technologies with the highest TRL, which would be available in the very short timeframe (Figure 1b).

While the screening process in Step 2 helps to narrow down the range of available options, it still results in 48 possible technology combinations (Table 4). In addition, some technologies listed in Table 4 are not yet tested with dry feces, hence the data basis is considered too poor to include in a quantitative comparison. Therefore the technologies microwave plasma gasification, hydrothermal gasification and hydrothermal carbonization were not taken into account in this evaluation. Neither was the combination of acidification and microbial fuel cell. With this constraint 18 combinations remain. We compare these combinations against a number of decision criteria in radar plots as illustrated in Figure 1. Calculations assumed a RRP treating the waste of 860 people (based on an optimized transport system[13]), each producing 200 g feces and 1.27 L urine per day[17,23,26]. Details of the calculation can be found in the Supplementary Information (SI).

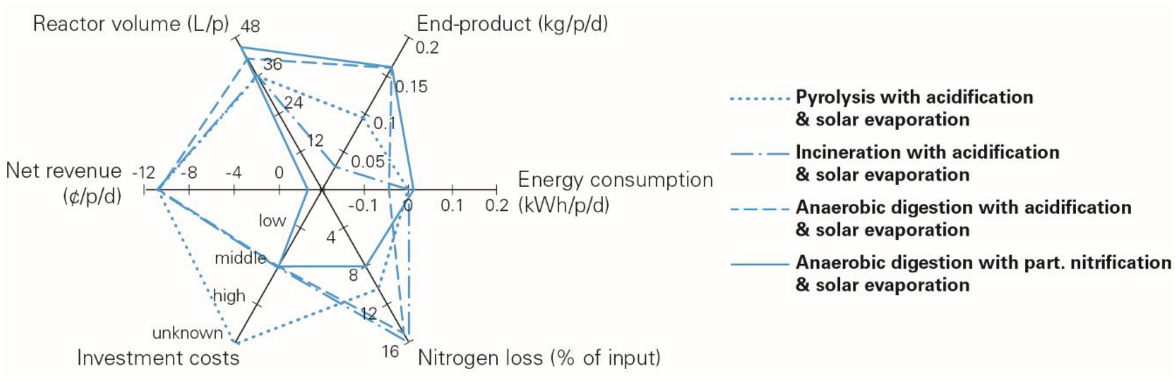
In this paper, three criteria are chosen to illustrate the selection process: (a) low reactor volume, (b) high TRL (above 5) or (c) energy efficiency. Of course, other criteria could be chosen depending on the local conditions. The strength of this methodology is not so much in identifying preferred technologies as it is in providing transparency in the decision-making process. The ranking of technology combination from each radar chart in Figure 1 depend on the preferences of the decision-maker, which will be influenced by the local situation (Step 5). For example, in very dense informal settlements, small reactor volumes may be the top priority (Figure 1a). Further ranking of these combinations would be done in Step 5 when decision-makers determine weighting of the remaining five criteria. For instance, in this case incineration with acidification & distillation may be preferred if low investment costs are a top priority, while pyrolysis with partial nitrification & distillation would be preferred if low atmospheric emissions are prioritized.



a)



b)



c)

Figure 1: Radar charts of options with best performance related to (a) small reactor volumes, (b) high TRL and (c) electrical energy efficiency. Since investment costs remain uncertain, investment costs are compared by ranking technologies into 4 cost categories: low (below US$10000/RRP), middle (US$10000-27500/RRP), high (above US$27500/RRP), and unknown (for very new technologies with low TRL). Note preferred values are at the center of the charts.

DISCUSSION

Once an implementation site is identified, the steps presented above would be followed by a process for ranking (and selecting) technologies according to the preference of local stakeholders. In ranking, local stakeholders will be making value statements by prioritizing different decision criteria, and thus influencing the optimization plots. For example, the radar plots presented for the RTTC case focused on optimizing for small reactor volumes, more mature technologies and energy efficiency. It is obvious from Figure 1, that there is not one combination of technologies which is optimized for all of these criteria. Normally, one would combine the results from Steps 3-4 when deciding how to prioritize decision criteria. For example, we expect areas with high population density to prioritize small reactors, while those with high availability of alternative energy sources may be less concerned about energy consumption. Additionally, the qualitative criteria derived from the STEEPLED analysis, but not illustrated in the radar plots, will influence the actual decision making. There are a number of multi-criteria decision support tools available that can be used with local decision-makers during this final step.

Since we are still in a very early phase of technology development, these comparisons primarily serve to highlight the strengths and weaknesses of different technology approaches and to indicate where the technologies must be improved in order to fulfill more of the important criteria. From Figure 1 and the underlying analyses, we draw the following conclusions:

1. Setting up very compact processes (Figure 1a) generally favors high-temperature processes. At the moment, we can predict neither low-cost, nor energy-efficiency for any of the extreme low-volume combinations identified. Combinations with partial nitrification and distillation offer the best opportunities for positive net revenue; however as a biological process it could be sensitive to climate variations and changes in influent composition. Acidification processes are also promising if the acid can be supplied reliably so that there are no safety concerns about using highly concentrated acids. However, the risks related to acids may be prohibitive of this method. Incineration processes result in lower costs and end-product outputs, however with higher nitrogen loss. Pyrolysis has a low TRL so it is possible that with further development costs could be brought down to make this option preferable for high-density areas. However, safe handling of the energy-rich gas it produces may be an issue.

2. Resource recovery from urine and feces is a young field of process engineering and only a few technologies exist at a high TRL (Figure 1b). For feces treatment, the only option is anaerobic digestion (although this option did not meet RTTC requirements); for urine they are stabilization with either biological nitrification or acid addition and volume reduction through distillation. It is important to keep in mind that biological processes can be sensitive to variable climate conditions (requiring more insulation and monitoring)

and generally require large reactor volumes. Of course, with further research and testing more technologies will reach high TRL levels and be ready for large-scale implementation.

3. The highest energy efficiency can be achieved with combinations of solar evaporation, but at high costs and large reactor volumes. Note that none of the evaluated options are self-sufficient and hence dependent on climate conditions for solar power. There are two ways to solve this problem: 1) some of the innovative feces treatment technologies investigated in the RTTC program are further developed to become energy self-sufficient, or 2) other existing technologies for urine treatment are further optimized with respect to energy-efficiency.

This paper contributes to the dialogue regarding co-evolution of technologies by introducing a macro-environmental analysis early in the design process. While an in-depth STEEPLED analysis is difficult to do without a specific context, this initial analysis and weighting of factors allow engineers and designers to focus on critical issues affecting potential global marketing and up-scaling of the technology. Often, engineers pursue technologies without considering the environment where they will be implemented. Despite the high degree of uncertainty illustrated in the present paper, an early STEEPLED analysis can help direct research towards real-life situations.

For real technology choices in the field, the quantified evaluation presented in Step 4 is very valuable if the technologies exist at a high TRL and can be optimized with respect to these quantifiable criteria. However, the STEEPLED analysis is also worthwhile for technologies with a low TRL. For these technologies the analysis can be used to highlight areas for improvement, for the quantitative as well as for the qualitative factors. Thus, the methodology is useful even when not all steps are completed, as in this case.

In any analysis, the results of a quantitative analysis (as shown in Step 4) should be weighed against the STEEPLED factors (Step 3) which have a qualitative effect, once a specific technology or context is known. For example, urine acidification appears to be optimal for high-density settlements, yet there are safety and ethical issues associated with operating such a process which may make this option less attractive. In general, the availability of O&M resources and political support are two qualitative factors which will play a critical role in the success of technologies in the field but which are difficult to quantify. However, awareness of these issues early in the process can result in more robust designs that are flexible within a variety of contexts and which require lower levels of operator capacity.

Finally, there are a number of trade-offs and challenges in matching fertilizer outputs to the macro-environmental context. The local climate will dictate the length and frequency of the growing season and hence fertilizer demand. A single planting season means a short window of local demand for fertilizer produced from the RRP. Output products in this case should therefore have a lower volume and longer storage life than might be necessary in areas with several planting seasons. Local fertilizer preferences will also dictate to some degree which nutrients are most profitable to recover. On the other hand, ethical responsibility to poor farmers and the environment may push for recovery of organic-rich soil conditioners rather than just high-price nutrients. In addition, risks for potential contamination from pharmaceutical compounds and personal care products will need to be considered. Because it is connected to so many other factors, production of a fertilizer will likely be hard to optimize, especially if there are other criteria competing for prioritization. Here, as with many environmental and socially responsible innovations, it is important to define the critical objectives to be achieved early in the design process and then carry them through the entire process.

The aim of the RTTC was to spur innovative thinking and design in the field of sanitation. It did this by setting high goals for treatment and resource recovery at a low cost, but without specifying technologies. It set rules while letting engineers and designers think freely. Of course, relaxing the design criteria (e.g. lower standards than drinking water for liquid discharges) would allow for inclusion of more technologies with high TRLs in the analysis. In any case, this paper offers a methodology that supports this widening of the design space, through the separation of waste stream flows, and a tool for narrowing down the field of options based on specific objectives and macro-environmental factors. We believe that the act of setting ambitious design requirements combined with the methodology outlined in this paper has the potential to foster the thinking that will lead to solutions to the global challenges we are facing today.

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SUPPORTING INFORMATION AVAILABLE

The supporting information (SI) contains short descriptions of the urine and feces treatment technology processes used in this analysis (Table 4) and reference values used to produce the radar charts (Figure 1). This information is available free of charge via the Internet at http://pubs.acs.org/.

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