Priority Addressment Protocol: Understanding the Ability and Potential of Sanitation Systems to Address Priorities

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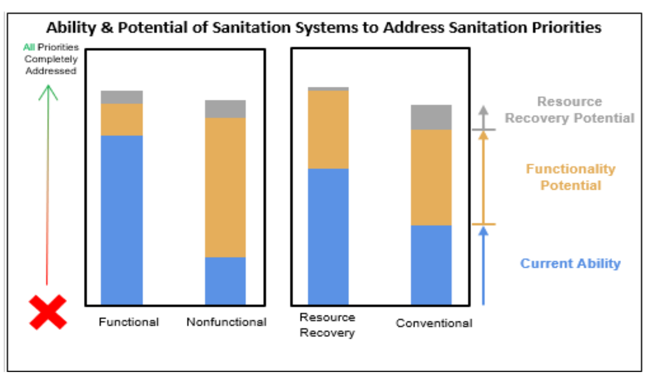

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Abstract

Sanitation acceptance is unlikely if user priorities are not addressed. However, sanitation systems are commonly implemented, especially in resource-limited communities, without incorporating local context. Understanding sanitation systems' abilities to address different priorities will further inform technology selection processes. Therefore, a protocol was created to identify priorities and measure how well sanitation systems address them, based upon their importance to a community. This protocol was applied to 20 community-based sanitation systems in India. Overall, 52 sanitation and 40 community priorities were identified; most, along with their relative importance, were case-specific and not yet identified in literature. Existing sanitation systems poorly addressed priorities. Nonfunctional systems addressed the fewest, but, if use and maintenance were improved, they had the potential to address priorities almost as well as functional systems. Resource recovery systems addressed the most priorities, but there was usually minimal benefit to adding all three resources to an existing system; biogas and water had greater potential to address more priorities than compost. This priority addressment protocol can help identify the most appropriate technologies and strategies to improve technology development and success.

Introduction

The United Nations' Sustainable Development Agenda encourages an increased focus on sanitation; however, sanitation still receives little attention from many governments and foreign assistance programs, and[1] 60% of the global population lacks access to functional or adequate sanitation.[2] Access is limited by many factors, especially high failure rates; 70% of sanitation systems fail within two years.[3] This issue is most common in resource-limited communities where sanitation use and acceptance is less likely to occur if user priorities are not addressed.[4,5]

Therefore, identifying priorities can improve success[6–8] and provide a strategy to increase universal sanitation access. However, sanitation systems are commonly implemented in resource-limited communities without incorporating local context, usually because implementers lack the resources or expertise to effectively assess priorities.[9] When priorities can be assessed, demand-responsive assessments are recommended but are resource-intensive.[10] So, implementers tend to use supply-driven[11] or limited[12] assessments, which commonly result in insufficient data. In addition, it is recognized that culture influences priorities,[9] but it is unclear to what extent communities with similar cultures share values. Also, most assessments focus on community-level needs,[13] but it is unknown if priority assessments should be context-specific or if overall community priorities can be translated to different projects, such as sanitation or energy. Finally, the relative importance of identified priorities is usually not assessed,[14] but because not all priorities may be addressable, especially when resources are limited, processes to identify a community's most important priorities can focus implementation efforts. Overall, there is a need to evaluate the usefulness of different types of priorities and focus on important priorities to maximize data quality while minimizing data collection requirements.

Further complicating the issue of failure, the ability of sanitation technologies to address priorities is not well known. In most sanitation monitoring efforts, implementers evaluate outcomes (e.g., functionality,[15] health[16]), usually without direct comparisons to communities' priorities. Finally, there is a growing effort to measure the social sustainability of sanitation. Other research has proposed social indicators such as "acceptance" and "appropriateness to local context", but many of these indicators lack consensus, empirical validation, or clear measurement methods. Technology selection and monitoring processes could be better informed if implementers could analyze and quantify how well existing systems, and potential new sanitation technologies, address priorities. For example, sanitation systems that recover energy, water, or nutrients from wastewater (i.e., resource recovery systems) have been introduced as an option to increase priority addressment.[17] Some studies have analyzed potential benefits from resource recovery, such as by evaluating the ability of these technologies to meet Sustainable Development Goals at a large-scale[18] or [19]to offset costs,[20,21] but most do not evaluate potential benefits within the context of a community's goals and priorities. Also, given culture-specific, and possibly case-specific, priorities and given the many types of resource recovery technologies available, it can also be important to evaluate which resources (e.g., biogas) can address the most priorities.

Therefore, this research created a "priority addressment protocol" that identifies priorities and measures how well sanitation systems address them, based upon their importance to each community (Figure 1). This protocol was applied in 20 resource-limited cases in India with community-based sanitation systems to: (1) identify sanitation and community priorities; (2) evaluate the ability of existing sanitation systems to address priorities; and (3) analyze the potential of different conventional and resource recovery technologies to improve priority addressment. The results and new protocol can help identify the most appropriate sanitation systems and design improvements that can encourage greater sanitation acceptance, use, and success.

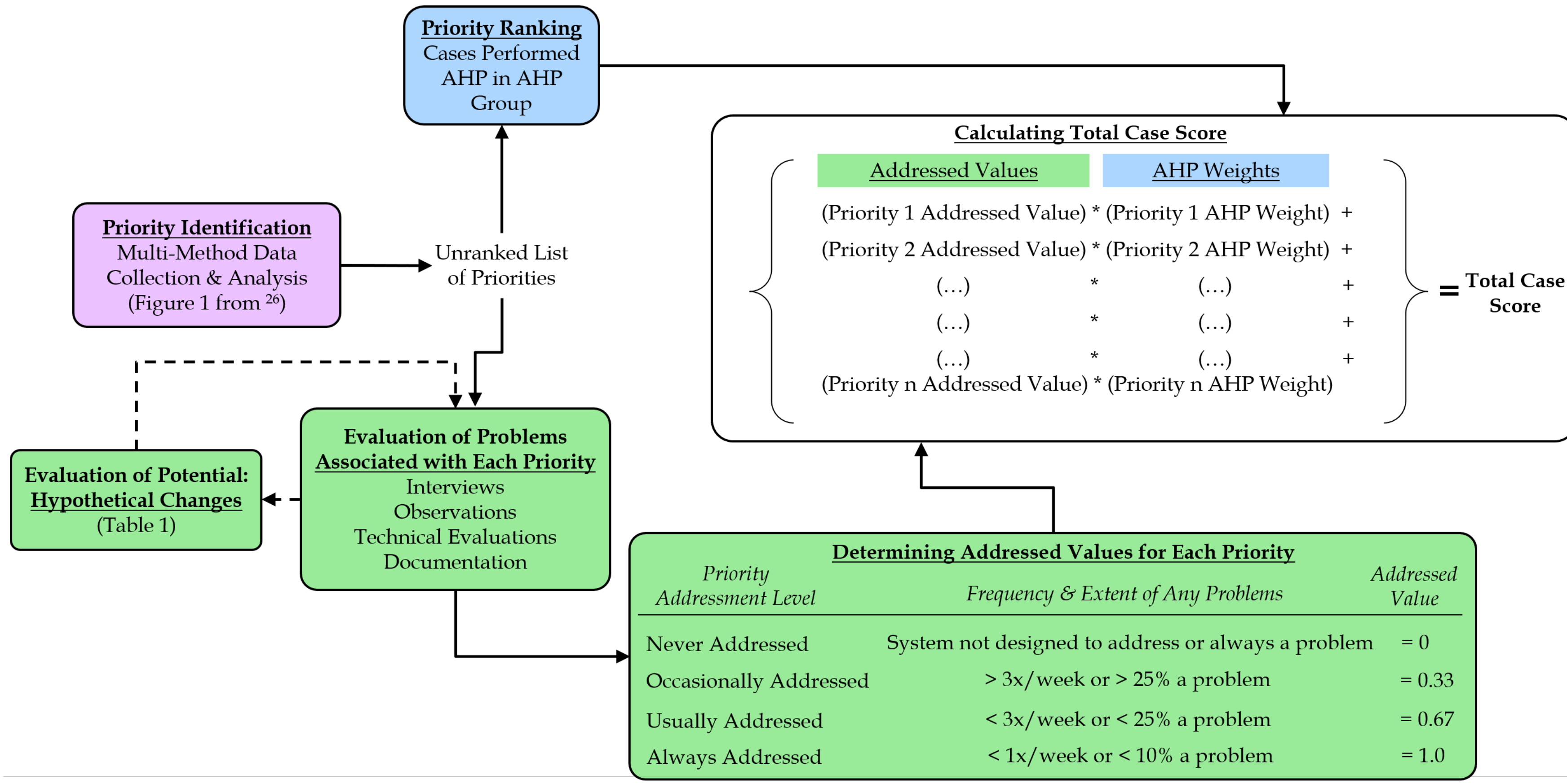


Figure 1. Overview of the priority addressment protocol used to identify priorities and evaluate the current ability and potential of different sanitation systems to address priorities. Purple indicates priority identification, blue indicates priority ranking, and green indicates priority addressment.

Methods

Case Descriptions & Priority Identification

Twenty peri-urban, low-income, slum resettlement cases in southern India were selected (Table S1), detailed in Davis et al.[22] Cases were resettled by government agencies to peri-urban areas to improve living conditions for India's lowest caste, but these resettlements still often lacked important infrastructure such as water or electricity. Each case had one centralized sanitation system. The systems served 800 to 1000 users, were implemented by external organizations, and were maintained by communities. Cases were selected to ensure comparable demographics, size, geography, and income but different sanitation technologies and functional statuses (Table S1). Priority identification used three qualitative data collection methods: interviews, focus groups, and photovoice. In photovoice, participants are usually given one to three days to take pictures in response to a prompt. In this research, participants had 24 hours to photograph their sanitation and community priorities; they then described the photos in a follow-up interview. [2322] Data collection aimed to capture a representative cross-section of case perspectives (balanced gender, age, and geographic representation and multiple community roles) and used door-to-door sampling in the morning, midday, and evening to include a range of lifestyles (e.g., employed and unemployed individuals). Data collection concluded when theoretical saturation was achieved (i.e., when no additional priorities were identified by subsequent participants) for each case. In total, 232 interviews, 171 photovoice follow-up interviews, and 20 focus groups (with 189 focus group participants) were completed across all 20 cases. Data was coded inductively (see Tables S2 and S3 for coding dictionaries) and triangulated between the three methods to identify one unordered list of sanitation priorities and one unordered list of community priorities per case. Priorities were then ranked using the Analytical Hierarchy Process (AHP) in each case by an additional focus group (called the AHP group). Each priority was assigned an AHP weight, which represents a priority's relative importance (a case's sanitation AHP weights sum to one). These methods are detailed in Davis et al.,[22] and all data collection followed protocol #16-0026 (approved by University of Colorado Boulder IRB in January 2016).

Priority Addressment

A priority addressment protocol was created to quantify the current ability and the potential of different sanitation systems to address priorities (Figure 1) and was evaluated in three scenarios (Table 1). The first, called the Current Scenario, evaluated how well a case's existing sanitation system—under existing use, maintenance, and performance conditions—addressed their sanitation and community priorities. The second, a hypothetical scenario called the Intended Design Scenario, evaluated how well an existing sanitation system *would* address priorities *if the system was functional*. The third, also a hypothetical scenario, called the Added Resource Recovery Scenario, evaluated how well a sanitation system with resource recovery *would* address priorities *if the system was functional and designed to recover biogas, water, and compost*.

Table 1. Description of Current, Intended Design, and Added Resource Recovery Scenarios.

Scenario	Technology Type	System Status
Current	Existing	Functional or nonfunctional (based on existing system and current use, operation, and maintenance)
Intended Design	Existing	Functional; made hypothetical changes to existing system (from Current Scenario) such that it became functional
Added Resource Recovery	Resource Recovery; made hypothetical changes to existing system such that it had full resource recovery (biogas, water, compost) capability	Functional; made hypothetical changes to existing system (from Current Scenario) such that it became functional

In the Current Scenario, there were five functional conventional, five nonfunctional conventional, five functional resource recovery, and five nonfunctional resource recovery systems (Table S1). Functional status was defined using three criteria: the sanitation system was (1) compliant with local regulations[24] for pH and chemical and biochemical oxygen demands, determined from effluent water quality tests; (2) adequately maintained, determined by triangulating data from observations, documentation (e.g., maintenance manuals), and system manager interviews; and (3) used continuously by more than 75% of the intended population, determined by triangulating data from observations, documentation (e.g., monitoring reports), and community member and system manager interviews; 75% was selected because health benefits increase significantly when the majority of a case's population is using toilets[25,26] and all cases with regulatory-compliant systems had greater than 75% use (Figure S1).

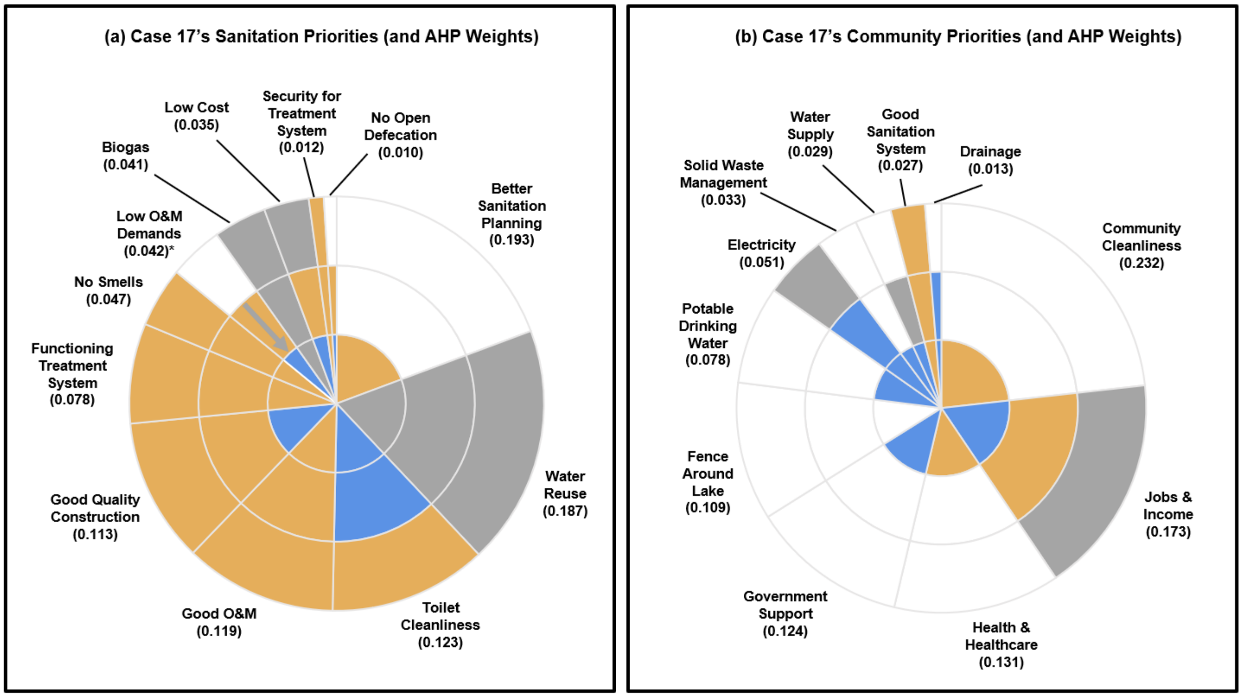
Priority addressment data was collected using interviews, technical evaluations, and observations. An average of six interviews, with community members and system managers, were conducted per case (Table S4), focusing on how often the community typically experienced problems with each priority. Technical evaluations assessed the sanitation system's construction quality, effluent water quality, odor, and cleanliness. Researchers observed system use and maintenance along with community life, such as status of roads and housing; on average, seven hours of observations were completed per case. Interview transcripts and observation notes were deductively coded[27] for design features and ongoing problems by two independent coders. Based on this information, each priority was assigned an "addressed value" to characterize the ability of the sanitation system to either always (1), usually (0.67), occasionally (0.33), or never (0) address that priority (Figure 1).

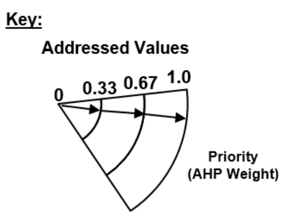
In the Intended Design Scenario, each addressed value was re-evaluated based on this scenario's hypothetical changes (Table 1) and the priority (Tables S5 and S7). In summary, an addressed value: (i) remained or increased to always addressed (i.e., 1.0) for priorities that could be completely addressed if the existing sanitation system was functional (e.g., *Toilet Cleanliness*); (ii) increased by one addressment level (e.g., from occasionally, 0.33, to usually, 0.67, addressed) for priorities that could be partially addressed by sanitation but may also be influenced by other non-sanitation factors (e.g., *Health & Hygiene*); or (iii) remained unchanged from the Current Scenario for priorities that could only be addressed with non-sanitation related changes or sanitation system design changes (e.g., *Individual Septic Tanks*).

In the Added Resource Recovery Scenario, each addressed value was re-evaluated, based on this scenario's hypothetical changes (Table 1) and the priority (Tables S6 and S8). In summary, an addressed value: (i) remained or increased to always addressed for priorities that could be completely addressed if the existing sanitation system was functional and recovering biogas, water, and compost; (ii) increased by one addressment level for priorities that could be partially addressed by resource recovery but may also be influenced by other non-sanitation factors; (iii) decreased by one addressment level for priorities that could be negatively affected by adding resource recovery but may also be influenced by other non-sanitation factors; or (iv) remained unchanged from the Intended Design Scenario for priorities that could only be addressed with non-sanitation related changes or other sanitation system design changes.

Finally, a "total case score" was calculated for each case's sanitation and community priorities (Figure 1). Each priority's addressed value was multiplied by its AHP weight. Then the weighted, addressed values were summed. The maximum total case score is 1, which means that all priorities are always addressed; the minimum is 0, which means that no priorities are ever addressed. Higher scores mean that more priorities and/or more of the most important priorities were addressed. To compare total case scores, one-way analyses of variance were performed at a 95% confidence level (α=0.05).[28]

Case 17's Total Case Sanitation Scores. Case 17 is a representative example. It had 12 sanitation priorities with AHP weights ranging from 0.010 to 0.193 (Figure 2a). With an existing nonfunctional conventional sanitation system in the Current Scenario: *No Open Defecation* (AHP weight=0.010) was always addressed (i.e., addressed value=1.0) because 88% of the community used the sanitation system; *Toilet Cleanliness* (AHP weight=0.123) was usually addressed (i.e., addressed value=0.67) because households reported cleanliness issues on average twice a week; *Good Quality Construction* (AHP weight=0.113) and *Low Cost* (AHP weight=0.035) were both occasionally addressed (i.e., addressed value=0.33) because the sewers were incorrectly constructed, which increased O&M costs by approximately 50%; the other eight were never addressed (i.e., addressed value=0). The AHP weighted sum of the 12 addressed values resulted in a Current Scenario total case sanitation score of 0.15 (Figure 2a), which was low because most priorities were not addressed by the existing system, especially those priorities most important to the case (e.g., *Better Sanitation Planning* and *Water Reuse*, with the highest and second highest AHP weights of 0.193 and 0.187, respectively).





	Total Case Scores	
Scenarios	Sanitation (a)	Community (b)
Current:	0.15	0.19
Intended Design:	0.62	0.39
Added Resource Recovery:	0.84	0.48

Figure 2. Case 17 presents a representative example for how the priority addressment protocol was applied to determine the extent that sanitation priorities (a) and community priorities (b) were addressed in each scenario. Colors represent how well each priority was addressed or could be addressed in the Current (blue), Intended Design (orange), and Added Resource Recovery (grey) scenarios. A wedge's height (color fill) represents a priority's addressed value for each scenario, where zero is never addressed, 0.33 is occasionally addressed, 0.67 is usually addressed, and 1.0 is always addressed. Stacked wedges for each priority are additive, even between scenarios; for a given priority, stacked colors indicate that subsequent scenarios improved priority addressment. For example, the community priority *Jobs & Income* has an AHP weight of 0.173 (wedge width) and addressed values of 0.33 for the Current Scenario (blue), 0.67 for the Intended Design Scenario (stacked orange), and 1.0 for the Added Resource Recovery Scenario (stacked grey). The community priority *Good Sanitation System* has an AHP weight of 0.027 and addressed values of zero for the Current Scenario (no blue shown since it is unaddressed), 1.0 for the Intended Design Scenario (orange), and 1.0 for the Added Resource Recovery Scenario (no added grey because no change from the Intended Design Scenario). The grey arrow and * for *Low O&M Demands* indicates where the addressed value *decreased* from 0.67 in the Intended Design Scenario to 0.33 in the Added Resource Recovery Scenario.

In the Intended Design Scenario, the following hypothetical changes were made to Case 17's existing sanitation system such that it was maintained and used as intended by the original design: (i) a skilled operator performed all maintenance; (ii) sewer blockages were removed and grading was improved; (iii) treatment tank material quality was improved; (iv) sewer and treatment tank access lids were replaced; and (v) fence around the treatment system was repaired.

Accordingly, the system was then classified as functional because: (i) it became fully used (i.e., increasing use from 88% to 100%); (ii) it became properly maintained (i.e., increasing maintenance tasks performed from 11% to 100%); and (iii) it started to meet effluent water quality regulations. The hypothetical changes resulted in *No Open Defecation* remaining always addressed and six more sanitation priorities becoming always addressed: *Toilet Cleanliness, Good O&M, Good Quality Construction*, *Functioning Treatment System, No Smells,* and *Security for Treatment System. Low O&M Demands* and *Low Cost* changed from occasionally to usually addressed because the well-constructed, functional system would require less emergency maintenance. *Better Sanitation Planning* became occasionally addressed since good planning is positively correlated with sanitation system functionality.[29] *Biogas* and *Water Reuse* remained never addressed because the system was not designed to recover these resources. The Intended Design Scenario total case sanitation score was 0.62. The higher score showed that improving maintenance of the existing sanitation system could help address many of Case 17's most important sanitation priorities.

In the Added Resource Recovery Scenario, the following hypothetical changes were made to the existing system: (i) the system became functional (same changes as in Intended Design Scenario), and (ii) the existing system's design was altered to include resource recovery technologies for biogas (digester), water (toilet flushing and irrigation piping), and compost (on-site static piles). The seven sanitation priorities that were always addressed in the Intended Design Scenario remained always addressed. Three more became always addressed: *Water Reuse* and *Biogas* because the system's design was changed from having no to full (water, biogas, compost) resource recovery capability; *Low Cost* because income from the sale of biogas, water, and compost could offset O&M costs and because sludge production would likely decrease since desludging is the largest contributor to sanitation O&M costs.[30] Only one other sanitation priority's addressed value changed in this scenario: *Low O&M Demands* decreased from usually to occasionally addressed because resource recovery systems have more complex O&M needs, such as frequent biogas digester monitoring.[30,31] The Added Resource Recovery Scenario total case sanitation score was 0.84; this scenario had the highest score because recovering biogas, water, and compost could address more sanitation priorities.

Case 17's Total Case Community Score. There were 11 community priorities with AHP weights ranging from 0.013 to 0.232 (Figure 2b). In the Current Scenario, no community priorities were always addressed; *Electricity* and *Drainage* were usually addressed; *Jobs & Income, Government Support, Potable Drinking Water, Solid Waste Management,* and *Water Supply* were occasionally addressed; and *Community Cleanliness, Health & Healthcare, Fence Around Lake,* and *Good Sanitation System* were never addressed. The Current Scenario total case community score was 0.19. In the Intended Design Scenario, *Good Sanitation System* became always addressed because this system was hypothetically functional. *Community Cleanliness* and *Health & Healthcare* went from never to occasionally addressed because a functional sanitation system could partially reduce lake pollution and exposure to fecal pathogens.[32] *Jobs & Income* became usually addressed because a functional sanitation system could provide economic benefits of reduced health costs[33],missed workdays[34], and increased employment.[35] The other five addressed values remained unchanged. The Intended Design Scenario total case community score was 0.39. In the Added Resource Recovery Scenario, *Electricity* and *Jobs & Income* increased by one addressment level from the Intended Design Scenario because biogas could be used for electricity generation and because the recovered resources could be sold or used to reduce expenditures on energy, water, and fertilizer. *Water Supply* changed from occasionally to usually addressed because recycled water could reduce scarcity but not meet all water demands. The Added Resource Recovery Scenario total case community score was 0.48.

Results and Discussion

Each case's AHP group decided that the final unordered priority lists were valid and comprehensive. In nine cases, one sanitation or community priority was voiced by only one participant, but each AHP group confirmed that it was important. For example, in Case 7, the male operator was the only participant to voice *Security for Treatment System*, but the AHP group members shared this value. In eight cases, one AHP group member wanted to remove a priority, but the AHP group always chose to keep the full list. For example, during Case 14's AHP group, a 20-year-old community member wanted to remove *Water Savings* from the list, but older community members remembered earlier droughts and reinforced its importance.

Sanitation Priorities

On average, each case identified 12 sanitation priorities. Overall, 52 different sanitation priorities were identified (Table 2). Only six were very common (i.e., shared by 10 or more cases): *No Smells, Functioning Treatment System, Toilet Cleanliness, No Open Defecation, Safety & Dignity,* and *Water Reuse*. Additionally, 12 cases expressed at least one economic-related priority, either: *Low Cost, Income Generation, Micro-Loan Program, Jobs for Women,* or *Women's Empowerment*. Many are common to other peri-urban communities, who often express priorities related to system performance, maintenance, access, safety, and cost[13,36–38] and a willingness to adopt resource recovery (e.g., water reuse) systems.[39,40] The following less-common priorities have also been previously identified in the literature: *Good O&M,*[41] *Good Quality Construction*,[41] *Water Supply at Toilets,*[38] *Reduced Waiting Time,*[36] *Comfortable,*[37] *Child-Friendly Toilets,*[38] *Privacy,*[42] *Biogas,*[39] *Low Cost* [36] *Compost,*[39] *Health & Hygiene,*[13] and *Community Involvement in Planning*.[42]

Several sanitation priorities were shared by at least two cases but were identified for different reasons. For example, *Move Toilets Away from Kitchen/Prayer Room* was expressed in Cases 1, 7, and 15 because of cleanliness concerns and in Case 2 because of space concerns. *Western Toilets* was identified in Cases 4, 5, and 7 because the elderly struggled with squat-plate toilets and in Cases 6, 9, and 18 because community members wanted "modern" facilities. *Repair System Damage* was stated in Case 3 because of broken access covers, in Case 10 because of cracked pipes, and in Case 12 because of broken doors on toilet stalls. Due to smells and blockages in small, local sewer systems, Cases 1, 3, 8, 10, 16, and 17 wanted *Individual Septic Tanks* while Cases 9 and 19 wanted a *Direct Municipal Sewer Connection* instead of a local treatment system.

Additionally, cases ranked the shared priorities differently. The importance of the six most commonly expressed priorities varied between cases (Figure S2); for example, the rank of *Toilet Cleanliness* ranged from first (AHP weight=0.22) to ninth (AHP weight=0.04) among the cases. Also, 12 of the 20 cases had different priorities ranked first. The highest-ranked priorities were often those that cases perceived to have the greatest potential to benefit or disrupt their sanitation systems. For example, *Toilet Cleanliness* was ranked first (AHP weight=0.22) in Case 14 because most community members stopped using the toilets due to poor maintenance and uncleanliness. In contrast, Case 11 ranked *Water Supply at Toilets* first (AHP weight=0.26) because they wanted to keep their constantly available water supply, which was important for users. This shows that the priority assessments identified comprehensive lists of sanitation priorities and not only outstanding problems.

Many sanitation priorities were also case-specific; with many not yet identified in the literature. Although cases had major similarities (i.e., resource-limited slum resettlements in southern India with centralized treatment systems), 18 priorities were expressed only once (i.e., by one case) (Table 2), including *Water Savings, Jobs for Women, Child-Friendly Toilets,* and *Stop Antisocial Elements*. This is likely because valuation of sanitation is informed by community-level culture.[43,44] For example, Case 20 valued *Income Generation* for the whole community's benefit while Case 18 specifically valued *Jobs for Women* because both males and females recognized women's employment as beneficial. Additionally, priorities were case-specific due to different sanitation experiences. For example, Case 1 valued *Treat Kitchen Greywater* because community members had previously lived in a community with this capability. Case 10's operator was negligent, so they valued *Community O&M Training* for community members. Overall, finding case-specific priorities and AHP weights across cases with similar characteristics shows the need to complete context-specific assessments in every case.

Table 2. The 52 sanitation priorities identified across all 20 cases, and the number of cases that shared each priority. Priority definitions are in Tables S2 and S3. Priorities are grouped by Performance/O&M, Use & Access, Benefits, and Planning & Design for readability. The most commonly expressed priorities (shared by 10 or more cases) are highlighted in yellow and bolded. Priorities that could not be addressed by at least one case's existing system design are highlighted in grey and italicized. [R] denotes priorities that were influenced by resource recovery in the Added Resource Recovery Scenario.

Priorities Related to Performance/O&M		***Priorities Related to Use & Access***		***Priorities Related to Benefits***		***Priorities Related to Planning & Design***	
Priorities	**# of Cases**	**Priorities**	**# of Cases**	**Priorities**	**# of Cases**	**Priorities**	**# of Cases**
No Smells	16	**No Open Defecation**	14	**Water Reuse**[R]	10	*Treatment System Far Away*	7
Functioning Treatment System	15	**Safety & Dignity**	11	Biogas[R]	8	*Western Toilets*	7
Toilet Cleanliness	15	Water Supply at Toilets[R]	9	Low Cost[R]	8	*Individual Septic Tanks*	6
Good O&M	9	Visual Aesthetics	5	Compost[R]	6	*Increase Sewer Pipe Size*	5
No Sewer Blockages	9	*Reduced Waiting Time*	4	Health & Hygiene	1	*Move Toilets Away from Kitchen/Prayer Rooms*	4
Good Quality Construction	7	Comfortable	3	Income Generation[R]	1	*Bathing Facilities at Toilets*	2
Low O&M Demands[R]	5	*Multi-Use Area (Park)*	3	Jobs for Women[R]	1	*Central Location*	2
Security for Treatment System	4	*Sanitary Napkin Disposal*	3	Micro-Loan Program[R]	1	*Direct Municipal Sewer Connection*	2
Repair System Damage	3	Open 24 Hours	2	Water Savings[R]	1	*Move Manholes to Grade*	2
Government Support for O&M	2	Privacy	2	Women's Empowerment[R]	1	Better Sanitation Planning	1
Stop Shower Drain Clogging	2	Child-Friendly Toilets	1			Community Involvement in Sanitation Planning	1
Community O&M Training	1	Easy to Use	1			*Shade for Sanitation Caretakers*	1
Efficient & Functional Treatment System Pumps	1	Lights in Toilets[R]	1			*Treat Kitchen Greywater*	1
Treatment of Wastewater	1	Stop Antisocial Elements	1				
		Toilets in All Houses	1				

Current Scenario. Overall, the existing sanitation systems did not address priorities well (Figure 3). In all 20 cases, regardless of technology or status, no system always addressed all sanitation priorities (all scores were less than 1.0). The average Current Scenario total case sanitation score was 0.42. Since sanitation priorities were not assessed prior to system implementation in 17 cases (Figure 3), it is likely that the poor addressment occurred because priorities were unknown. Additionally, some were unaddressable, usually due to the system's design or nonfunctionality. Seventeen of the 20 cases had at least one unaddressable priority, with 13 cases having at least one in their top five most important priorities, usually ranked first. Fourteen priorities required significant planning and design changes that were too expensive or complex (Table 2). For example, in Cases 1 and 8, septic tanks were not installed because the government would only pay for a centralized treatment system; and in Cases 3, 10, 16, and 19, septic tanks were not installed due to groundwater contamination risk. Western toilets were too expensive in all seven cases (Cases 1, 4, 5, 6, 7, 9, 18). In Case 16, *Treatment System Far Away* could not be addressed because a cultural heritage site protected their desired location. Additionally, some cases valued resource recovery (*Compost, Water Reuse, Biogas*), but those priorities could not be addressed due to high costs (Cases 1, 3, 15), insufficient space (Cases 9, 20), or inadequate implementer design knowledge (Case 8).

Total case sanitation scores were lower for nonfunctional (average=0.18) than functional (average=0.66) sanitation systems because functional systems addressed more sanitation priorities (p=0.000). Case knowledge indicates that unaddressed priorities may be both a cause and an effect of system nonfunctionality. To help understand this relationship, all cases were re-analyzed as hypothetically functional in the Intended Design Scenario. In addition, of the Current Scenario functional systems, total case sanitation scores were lower for conventional (average=0.50) than for resource recovery (average=0.82) systems, so the Added Resource Recovery Scenario explored the potential of resource recovery

Intended Design Scenario. Overall, if the existing sanitation systems could function according to their design then they could address more sanitation priorities (Figure 3). With an average score of 0.75, all cases had a higher total case sanitation score in the Intended Design Scenario than in the Current Scenario (Table S9). Systems that were nonfunctional in the Current Scenario had large score increases, on average by 475% (Table S10). For example, Case 12's total case sanitation score increased from 0.35 to 0.82 because the existing nonfunctional resource recovery system hypothetically changed from: (i) 32% to 100% used, so income from user fees increased such that *Micro-Loan Program* became usually addressed; (ii) 7% to 100% maintained, so an operator performed maintenance and repaired the fence, such that *Water Supply at Toilets, Biogas, Toilet Cleanliness*, *Security for Treatment System,* and *Visual Aesthetics* became always addressed; and (iii) 0% to 100% of regulations met, so *No Smells* and *Functioning Treatment System* became always addressed. Systems that were already functional in the Current Scenario had smaller score increases, on average by 26%. For example, Case 11's total case sanitation score increased from 0.82 to 0.98 in the Intended Design Scenario because the existing functional resource recovery system hypothetically changed from 92% to 100% maintained, so small cracks in the digester were fixed such that *Biogas* became always addressed. No total case sanitation score was 1.0 in the Intended Design Scenario because no case had a system that, even when functional, could always address all of their sanitation priorities.

Added Resource Recovery Scenario. Hypothetically functional, full resource recovery systems resulted in the highest average total case sanitation score of 0.81. More sanitation priorities were addressed in the Added Resource Recovery Scenario than in the Current Scenario (p=0.000), but priority addressment was similar between the Added Resource Recovery and Intended Design scenarios (p=0.325) (Table S9). This suggests that there may be limited benefits to adding resource recovery to address sanitation priorities. In addition, although fewer resource recovery-related priorities were expressed by cases with existing conventional systems (average=2) than cases with existing resource recovery systems (average=4), conventional systems' scores increased more in this scenario because their resource recovery-related priorities could be met by adding or changing technologies.

For the 10 cases that already had some resource recovery, total case sanitation scores from the Intended Design to the Added Resource Recovery Scenario did not change in four cases (Cases 5, 9, 11, 14), increased in four cases (Cases 12, 13, 18, 20, by an average of 6%), and decreased in two cases (Cases 2, 6, both by 2%) (Figure 3). Systems with existing resource recovery technologies were already well-aligned with each case's priorities, so adding greater resource recovery capability in this scenario had minimal benefits. For example, in the Intended Design Scenario, Case 11's functional DEWATS system (with a biogas digester and onsite irrigation) produced biogas, which was sold as cooking fuel, and recycled water, which irrigated a profitable vegetable farm. Therefore, no further resource recovery was needed to address Case 11's priorities.

However, for 4 of these 10 cases, additional resources needed to be recovered to address priorities. For example, Cases 12, 18, and 20 valued *Compost*, which was never addressed by their existing DEWATS design that only recovered biogas and water. While compost recovery would increase O&M tasks, total case sanitation scores increased when compost recovery was hypothetically added because Case 12 valued *Compost* more than *Low O&M Demands* (AHP weights of 0.05 and 0.01, respectively), and Cases 18 and 20 did not value *Low O&M Demands.* In contrast, total case sanitation scores decreased for Cases 2 and 6 due to the hypothetical addition of compost recovery; compost could not address any priorities in either case, and it instead decreased the addressment of *Low O&M Demands* due to the increase in composting O&M tasks.

The total case sanitation scores for the other 10 cases, which had existing conventional systems that were hypothetically changed to include full resource recovery, did not change in two cases (Cases 7, 16), increased in seven cases (Cases 1, 3, 8, 10, 15, 17, 19, by an average of 25%), and decreased in one case (Case 4 by 0.2%) from the Intended Design Scenario to the Added Resource Recovery Scenario. The two cases with unchanged scores expressed no resource recovery-related sanitation priorities. For seven cases, though, a resource recovery system better addressed priorities than conventional systems. For example, *Water Reuse* in Cases 1, 3, and 17 was only addressed in the Added Resource Recovery Scenario since these cases' existing systems were not designed to recycle water. *Low Cost* in Cases 3, 4, 10, 17, and 19 became better addressed because resource recovery provides opportunities for cost savings (e.g., reducing expenses due to recycling water) and income generation (e.g., selling biogas). Finally, in Case 4, adding resource recovery resulted in a trade-off because it could reduce costs while also increasing technological complexity and maintenance burdens; since *Low O&M Demands* (AHP weight=0.08) was valued more than *Low Cost* (AHP weight=0.05), the total case sanitation score decreased.

An important consideration is that some communities reject resource recovery because the benefits do not outweigh the additional maintenance costs.[37,39] This is highlighted with the three cases that had total case sanitation scores that decreased in this scenario. Additionally, there can be psychological and cultural barriers towards adopting resource recovery systems; for example, composting toilets are viewed as a sign of poverty[37] and water and fertilizer from sanitation systems are considered unclean.[20,45,46] While adding resource recovery increased the scores for the majority of cases, all scenario's total case sanitation scores were still less than one (Figure 3), demonstrating that there are still opportunities to improve service delivery, technology development, and priority alignment.

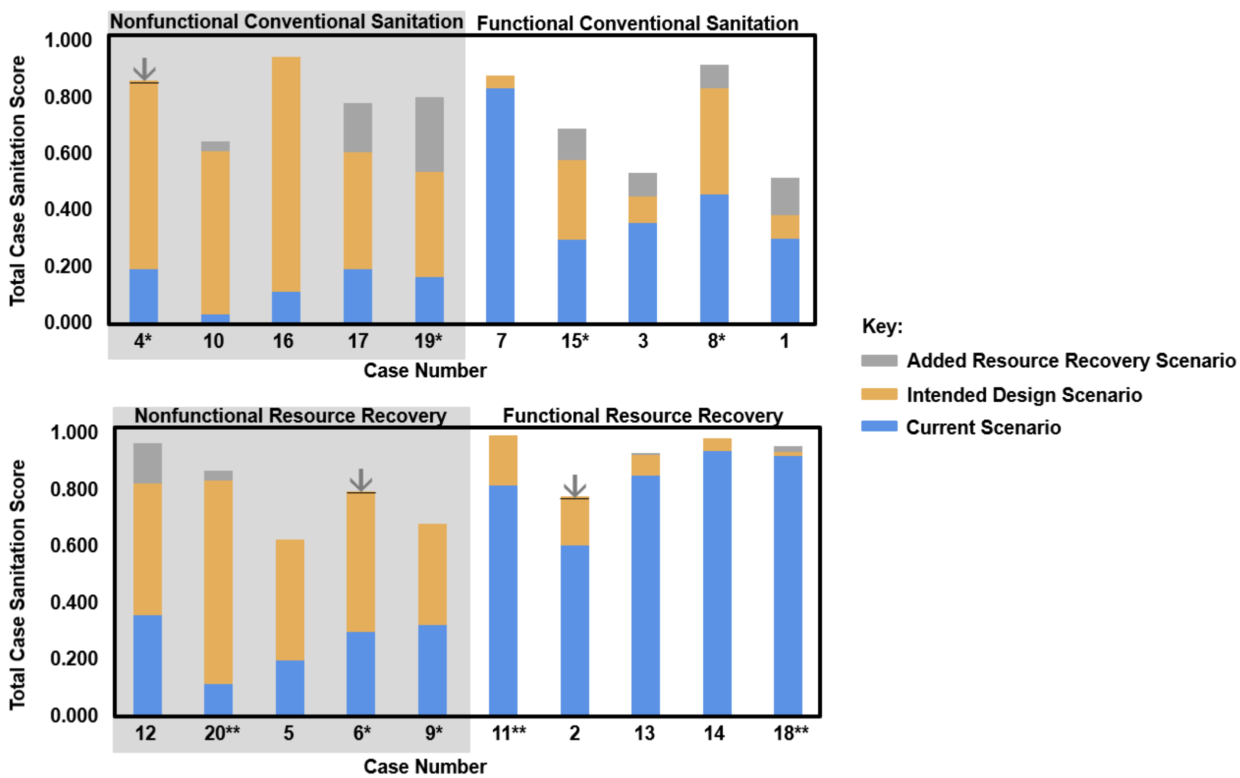


Figure 13. Comparison of the ability of the Current Scenario (blue) and potential of the Intended Design (orange) and Added Resource Recovery (grey) Scenarios to address sanitation priorities. Stacked columns are additive between scenarios. The cases are grouped based on each case's Current Scenario system status (functional or nonfunctional) and technology type (conventional or resource recovery). An arrow indicates when a case's score decreased (by 0.03 or less) between the Intended Design and Added Resource Recovery Scenarios, which happened in three cases (4, 6, 2), and the black horizontal line shows the decreased score value. A * next to the case number indicates that a limited prior priority assessment (on only community priorities) was conducted by implementers; ** indicates that a comprehensive prior priority assessment (on community and sanitation priorities)was conducted by implementers.

Community Priorities

On average, each case identified 13 community priorities; a total of 40 different community priorities were identified from the 20 cases (Table S11). The 12 most commonly expressed priorities have been previously identified: *Community Cleanliness,*[13] *Good Sanitation System,*[47] *Drainage,*[36] *Solid Waste Management,*[13] *Jobs & Income,*[13] *Water Supply,*[42] *Education,*[13] *Health & Healthcare,*[13] *House Improvements,*[13] *Potable Drinking Water,*[42] *Government Support,*[13] and

Cooking Fuel.[36] The importance of these priorities also varied greatly between cases (Figure S3). The less-common community priorities were often case-specific, with 16 expressed by one case apiece, including *Micro-Loans for Women, Land Ownership,* and *Library* (Table S11), and were not yet identified in the literature. Priorities were likely different between cases due to differences in existing infrastructure and services. For example, only Case 1 valued *Graveyard* since they were the only case without one. Overall, only 11 community priorities were related to sanitation or resource recovery: *Community Cleanliness, Good Sanitation System, Jobs & Income, Water Supply, Health & Healthcare, Cooking Fuel, Eradicating Pests, Electricity, Overall Community Development, Micro-Loans for Women,* and *Women's Empowerment*.

Current Scenario. Community, more than sanitation, priorities were poorly addressed in the Current Scenario. The average total case community score was 0.31 (minimum=0.17; maximum=0.55) (Figure S4). The low scores were expected since 29 community priorities were unrelated to sanitation (e.g., *Road Improvements*). Also, all priorities related to sanitation or resource recovery, except *Good Sanitation System*, were influenced by multiple factors and could not be fully addressed by a sanitation system alone (e.g., *Health & Healthcare*). Similar to sanitation, more community priorities were addressed by functional than nonfunctional sanitation systems (score averages of 0.37 and 0.25, respectively).

Intended Design Scenario. Hypothetical functionality had minimal benefits. The total case community scores remained low across all 20 cases (average=0.44) in this scenario because many community priorities do not relate to sanitation and most sanitation systems are not designed to meet multiple infrastructure or social needs. However, hypothetically changing the 10 existing nonfunctional systems to become functional allowed them to address more community priorities (scores increased by 98% on average) (Table S12); they could always address *Good Sanitation*

System and better address *Community Cleanliness, Health & Healthcare, Eradicating Pests, Jobs & Income,* and *Overall Community Development*. Only two of the 10 cases with existing functional systems had total case community scores change in this scenario (Cases 2, 11). The scores increased because hypothetical digester repairs resulted in biogas production and sales; therefore, *Electricity, Cooking Fuel,* and *Jobs & Income* could be better addressed.

The protocol's score evaluation should be updated as more research on possible impacts becomes available and should be as context-specific as possible. There are mixed findings on the amount of benefits from sanitation (some studies show a range of benefits[25,32,34] while some find no impacts[48,49]), and not all benefits can be realized in certain contexts (e.g., a market for biogas needs to be available for it to have an economic benefit). Due to currently limited information, two main assumptions were used. First, since the uncertainty analysis demonstrated that the value of a single priority's addressment score alone was relatively uninfluential on the total case score (Figure S5), an assumption of maximum potential benefits from sanitation, as found in literature, was used (e.g., functional sanitation systems and resource recovery positively influence health and income). Second, it was assumed that all priorities associated with a hypothetical change would be simultaneously improved. This large improvement would be unlikely (e.g., since there is a limited amount of biogas that can be produced from small sanitation systems), but this second assumption was used because it is uncertain which priority, over other more and less important priorities, would be addressed and because total case scores and results were insensitive to this calculation approach (i.e., the scores were equal or decreased by only 2% ± 6% when only one versus multiple related priorities' addressed values were changed) (Figure S5).

Added Resource Recovery Scenario. In this scenario, the average total case community score was 0.49, the highest of the three scenarios. However, this scenario's individual case scores were not significantly different from the Intended Design Scenario's scores (p=0.212) (Table S13); there was no change in scores for three cases and less than a 20% change for the other 17 cases (Figure S4). Scores increased in all 10 cases that had conventional systems hypothetically changed to resource recovery systems (scores increased 19% on average) and in seven cases that already recovered one resource and were hypothetically changed to recover two additional resources (scores increased 8% on average). The scores did not change for three cases because their priorities were well-addressed by the existing designs, which already included two or three types of resource recovery. Although these scores did not change, there could be a benefit from additional resource recovery not quantified with the "always addressed" definition, such as the benefit of reducing resource scarcity). Overall, the minimal changes in scores suggest that there might be diminishing benefits of adding multiple types of resource recovery. Of the three resources, biogas and water had greater potential to address more sanitation and community priorities than compost. For example, *Biogas*, valued in nine cases, could partially address *Electricity* in eight cases and *Cooking Fuel* in 10 cases. *Water Reuse*, valued in 10 cases, could partially address *Water Supply* in 17 cases. *Compost* was valued in six cases, but since all cases lacked agricultural opportunities, no community priorities could be addressed by compost.

Implications and Priority Assessment Importance

Overall, low total case scores for the Current Scenario highlight that existing systems poorly address priorities because priorities were unknown or unaddressable or because systems were nonfunctional. Score increases in the hypothetical scenarios demonstrate that improvements to sanitation technology design and service delivery could address more priorities. This shows the need to evaluate why systems are failing using a systematic approach. Additionally, most priorities and rankings were case-specific. Only nine (Cases 4, 6, 8, 9, 11, 15, 18, 19, 20) had their priorities evaluated prior to sanitation implementation, with only three (Cases 11, 18, 20) having both sanitation and community priorities assessed using a diversity of community perspectives.[22] This shows the importance of implementers conducting assessments in each case.

Prior priority assessments, though, were not correlated with system status, system technology, or total case scores within the 20 cases (Figures 2 and S5). Knowing priorities is still expected to be important,[9,50] so this lack of a trend may be because assessments focused exclusively on problems. For example, many of the prior evaluations were limited to community priorities. In this study, it was found that community priorities mostly reflected a snapshot of current problems; 85% of community priorities were current problems (unaddressed). This is likely because cases lacked access to basic infrastructure and services. In contrast, sanitation priorities included problems and existing capabilities that cases wanted to keep; only 55% of sanitation priorities were problems (unaddressed). Consequently, assessing overall community priorities may miss existing services and infrastructure that could be a problem in the future and must be maintained. Therefore, priority assessments should be context-specific and encourage participants to identify priorities that are not just current problems so that both short-term and long-term needs can be considered.

Further, no case's prior assessment identified the most important priorities. While ranking priorities can have limitations,[51] knowing their relative importance can identify interventions that maximize incentives for a case to use and maintain a sanitation system. Also, it helps to quantify addressment, which can be used to compare sanitation systems' social sustainability. While many frameworks include indicators for social sustainability, such as acceptance,[52,53] satisfaction,[54,55] appropriateness to local context,[56] and cultural sensitivity,[57] these frameworks call for method development to measure these social indicators, do not define the indicators (e.g., do not state how to measure them), or state that indicators should be adapted to local context without providing that guidance. This study's priority addressment protocol uses concepts from existing social indicators, such as acceptance and satisfaction, to identify specific ways that sanitation systems could be improved to increase social sustainability. The protocol does this by combining context-specific priorities (i.e., individual indicators determined by communities themselves) into one quantitative indicator. This protocol and resulting social sustainability indicator (i.e., total case score) was used to evaluate sanitation; it can also be used to evaluate a diverse range of engineering systems (e.g., drinking water, energy). Researchers and implementers can use this study's results and priority addressment protocol to elucidate which technologies and strategies minimize tradeoffs and meet the most priorities long-term.

Supporting Information

Details of the methods and additional tables and figures.

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