# Analyzing sanitation sustainability assessment frameworks for resource-limited communities

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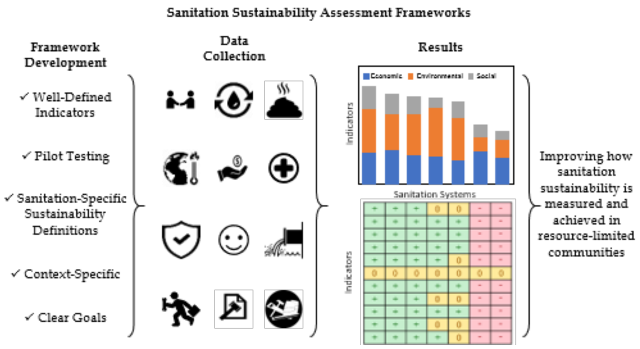

## Abstract

Diverse and numerous sanitation sustainability assessment frameworks have been created to enhance the ability of systems to provide safe sanitation services, especially in resource-limited contexts. However, many go unused while new frameworks are developed and high sanitation system failure rates persist. To better support the Sustainable Development Goal around global sanitation, there is a need to better understand how sanitation sustainability is defined and measured and the potential advantages and disadvantages of existing assessment frameworks. A subset of existing sanitation sustainability assessment frameworks was reviewed after applying each to evaluate multiple successful and failed community sanitation systems in India. Overall, the evaluated frameworks did not share a sanitation sustainability definition or core set of essential indicators. Many indicators lacked clear definitions and guidance on data collection and analysis. When evaluating framework effectiveness, differentiations between successful and failed cases varied greatly between frameworks. Potential improvements include indicator pilot-testing, to verify measurement feasibility and that they provide expected results; context-specific weightings; and project-specific framework selection. Clarifying and improving sanitation sustainability assessment frameworks could increase their effectiveness and use, leading to better decision-making and improved public and environmental health, economic viability, and sanitation use and acceptance.

**Keywords:** Sanitation, sustainability framework, assessment, resource-limited communities

## Introduction

More than 60 percent of the global population lacks access to safe sanitation.[1] To improve sanitation system success and access, researchers and practitioners have developed numerous sanitation sustainability assessment frameworks, especially for resource-limited contexts.[2–4] However, sanitation system failure rates are unacceptably high,[5] and new frameworks are still being developed. Improving the use and potential effectiveness of assessment frameworks could address this continued failure. To improve global sanitation sustainability there is a need to understand how sanitation sustainability is defined and measured.

In particular, first, many sustainability definitions are incomplete or unclear.[2,6] For example, frameworks often evaluate a sanitation system's level of service,[1,7,8] so definitions should include service provision. Also, while frameworks that evaluate the three pillars of sustainability are being increasingly developed,[9–13] many existing frameworks focus on only one pillar. For example, numerous frameworks use life cycle assessment principles to evaluate environmental impacts;[14–19] others use life cycle costing methodology to quantify economic impacts;[20–24] and others assess social impacts.[25–27] Overall, there is a need to measure and define sustainability consistently and uniformly.[2,6]

Second, the sanitation field does not have a universal set of sustainability indicators, likely because of frameworks' varied sustainability definitions and experts' disagreement on which indicators are most appropriate.[28,29] So many existing frameworks have their own unique set of indicators that lack consistent measurements and definitions. For example, some indicators are extremely difficult to measure (e.g., *Number of Diarrheal Diseases Annually*[30]), are too context-specific (e.g., *Post-Flood Latrine Repairs*[31]), or are too general (e.g., *Export of Problems in Time and Space*[2]). Also, different frameworks use different measurement approaches for the same indicator (e.g., *System Performance* measured with by concentration[32] or percent removal[33] of different water quality parameters). Since it is infeasible to collect data on all possible indicators,[34] there is a need to identify which indicators and combinations of indicators are most useful and measurable within resource limitations.

Third, frameworks are structured differently and must be applied appropriately. For example, they support decisions and data processing in different ways. Frameworks that use: qualitative methods typically discuss each indicator separately to valuate one sanitation system;[35–38] semi-quantitative methods typically evaluate whether a sanitation system's impacts were better, equal to, or worse than a baseline;[33,39,40] and quantitative methods typically employ multi-criteria decision analysis (MCDA) to aggregate quantitative data into a single-score per sanitation system.[41–45] In addition, there are different frameworks for different project phases. Monitoring-based frameworks are intended to qualitatively evaluate and discuss impacts and tradeoffs within a single system[35,46–48] or track an existing system's change over time.[36,49] Comparison-based frameworks are intended to compare multiple systems, to each other or to a baseline, by assessing indicators in relative terms and are often used for technology selection.[33,39,50,51] These various types of frameworks are often used interchangeably, showing a need to better understand the capabilities, benefits, drawbacks, and appropriate applications of existing frameworks.[34]

To this end, a subset of existing frameworks intended for resource-limited contexts (Table 1) was comprehensively evaluated, by applying each to real case studies (i.e., existing successful and failed community-based sanitation systems), to help determine the most effective definitions and measures of sanitation sustainability. The goal of this analysis was to gain insight on the most effective elements of existing, diverse frameworks and to translate any limitations into recommendations for the improvement of future framework development and use. The frameworks' various indicators and their measurements required a large range of data, so 12 resource-limited communities in India with small-scale sanitation systems, where extensive data was already available[25,52] and additional data could be collected, were chosen (see Table S1 for community details). The most effective data (i.e., indicators to differentiate systems with distinct outcomes), data processing, and results presentation approacheswere examined. Also, the implications of differing sanitation sustainability definitions and how stakeholders can identify and adapt a framework based on project-specific goals were discussed. This analysis can improve how sanitation sustainability is measured, and ultimately achieved, in resource-limited communities.

## Methods

### Framework Selection and Description

Existing sanitation sustainability assessment frameworks were identified from the literature and by consulting water, sanitation, and hygiene (WASH) practitioners. A subset of these frameworks (Table 1) were selected for further analysis based on three criteria. Each had to: take a holistic evaluation approach and include, at a minimum, indicators associated with social, economic, and environmental pillars, to be consistent with common sanitation sustainability definitions; have an explicit sanitation focus in resource-limited communities; and clearly define its objective (e.g., monitor community sanitation systems over time. Since the goal was to gain insight into framework application and development improvements, instead of attempting to comprehensively evaluate all existing frameworks, a subset of the frameworks that met these criteria was chosen. Ultimately, six sanitation sustainability frameworks were selected that captured a range of author-affiliated organizations (e.g., researchers, practitioners), complexity and diversity of indicators (e.g., number and range of different social indicators), data processing methods (e.g., MCDA, qualitative), and intended applications (e.g., planning, post-implementation) to help represent the diversity of frameworks (Table 1).

**Table 1.** Summary of the six selected sanitation sustainability assessment frameworks, representing a range of author-affiliated organizations, objectives, data processing methods, sustainability definitions, and indicators.

| Framework | Objective/Purpose | Intended Project Phase | Unit(s) of Analysis | Data Processing Method | Framework Testing | No. of Indicators | Indicator Categorization | Citation |
|---|---|---|---|---|---|---|---|---|
| TechSelect 1.0: Technology Assessment for Wastewater Treatment Using Multiple-Attribute Decision-Making (**TechSelect**) | To evaluate and rank sanitation technology alternatives to select appropriate technologies | Planning (Technology Selection) | Small-scale sanitation systems (especially high-rises in India) with unspecified toilet connection (possible for household or community toilets) | Quantitative indicator measurements (scale: 0 to 1) aggregated into single-score using multi-criteria decision analysis with six expert weighting options | Applied to hypothetical scenarios and technologies | 12 | Economic, Environmental, Social | 42,53,54 |
| Stockholm Environment Institute Sustainability Criteria (**SEI**) | To help municipalities evaluate the relative sustainability of technologies compared to an existing, conventional sewered treatment system | Planning (Technology Selection and System Sizing) | Onsite small-scale and large-scale municipal sanitation systems with unspecified toilet connection (possible for household or community toilets) | Semi-quantitative indicator measurements (scale: --, -, 0, +, ++) used to compare system to the "0 alternative" (i.e., baseline) | Applied to hypothetical scenarios and technologies | 34 | Economic, Environmental, Social, Health, Technical | 33 |
| Skat Foundation and WaterAid Technology Applicability Framework (**TAF**) | To provide a decision support tool to evaluate the sustainable application of a potential or implemented technology, considering the roles of and impacts on beneficiaries, implementers, and governments | Planning (Technology Selection) or Post-Implementation (System Improvements and Program Effectiveness) | WASH technologies (including sanitation systems) of any scale with unspecified toilet connection (possible for household or community toilets) | Semi-quantitative indicator measurements (absolute scale of supportive, unknown, or hindering characteristics) | Revised after piloted with existing systems | 18 | Economic, Environmental, Social, Institutional, Technical | 39,55,56 |
| Assessing the Sustainability of Small Wastewater Treatment Systems: A Composite Indicator Approach (**CIA**) | To assess the global sustainability of small-scale sanitation systems post-implementation | Post-Implementation (System Improvements) | Small-scale sanitation systems with unspecified toilet connection (possible for household or community toilets) | Quantitative indicator measurements (scale: 0 to 1) aggregated into single-score using multi-criteria decision analysis with expert weighting | Applied to hypothetical scenarios and technologies | 17 | Economic, Environmental, Social | 44,57 |
| UNICEF Sustainability Checks (**UNICEF**) | To monitor and evaluate the impacts of community-led total sanitation programs that aim to achieve open defecation free districts through behavior change and latrine construction | Post-Implementation (System Improvements and Program Effectiveness) | Household latrines resulting from community-led total sanitation latrine construction programs in any size community | Qualitative and quantitative indicator measurements; Qualitative discussion of impacts | Revised after piloted with existing systems | 20 | Economic, Environmental, Social, Institutional | 36,37,49 |
| Centers for Disease Control and American Red Cross Sustainability of water, sanitation and | To monitor and evaluate the impacts of implemented integrated WASH interventions | Post-Implementation (System Improvements | Household latrines (and small-scale community water supply systems and hygiene education programs) | Qualitative and quantitative indicator measurements; Qualitative discussion of impacts | Piloted with existing systems | 11 | Economic, Environmental, Social | 35,58 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| hygiene interventions (**CDC/ARC**) | (following Hurricane Mitch in El Salvador, Guatemala, Honduras, and Nicaragua) | and Program Effectiveness) | | | | | | |

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## Real Cases Data Collection and Evaluation

The various indicators and their measurements required a large range of data. The cases included 12 resource-limited communities in India with small-scale sanitation systems (Table S1) where where extensive data could be collected. The communities were peri-urban, slum resettlements in Karnataka and Tamil Nadu, India. All had sanitation systems that served between 800 and 1000 individuals and were intended to be maintained by community operators. Each sanitation system's status (successful or failed) was previously determined;[25,52] in summary, a successful system was (1) used daily, exclusively, and correctly by at least 75 percent of the intended population; (2) maintained correctly and on-time; and (3) complied with local regulations. Of the ten successful systems, five were conventional sanitation systems intended to solely contain and treat wastewater; five were resource recovery systems intended to produce and recover biogas, compost, or water. Two extreme failure caseswere also included to help determine if framework results reflected the extreme contrast between distinctly successful and failed systems. Only a limited number of failed cases were included due to the difficulty of data collection from failed systems.

Data was collected by the first author, with the help of translators and research assistants trained in sanitation fieldwork, from May to August 2016, January to May 2017, and December 2018 to February 2019. In summary, previously collected data included: interviews, photovoice, and focus groups that elucidated local priorities for sanitation and the ability of sanitation systems to address those priorities and interviews with community members, operators, implementing organizations, and municipalities that discussed major causes of system success or failure.[25,52] Additional data needed to apply each framework included survey questionnaires with community members using questions provided in the sustainability frameworks to measure household expenses, willingness to pay, hygiene behaviors, open defecation free (ODF) verification processes, and availability of sanitation materials and financing. It also included documentation, researcher observations, and technical system evaluations that assessed construction quality, handwashing behavior, ODF verification, and system performance and validated interview and survey data. All data collection followed the approved Institutional Review Board protocol #16-0026.

Data analysis (i.e., indicator measurements and scoring) followed the methods described by each framework. When a framework had an indicator that was ambiguous (i.e., no indication of how to measure it), then literature and case data were used to define the indicator or to specify a metric and measurement scale (more details on adaptations are in the Supporting Information (SI) Section S2 and Table S2).

## Framework Evaluation

Each framework was evaluated individually. First, each framework's sanitation sustainability definition and objective were identified. Next, a framework's indicators were evaluated to determine how well they met the framework's objective and sustainability definition. Then, the framework was applied to the real successful and failed sanitation systems. This was done to determine (i) if and how any indicators needed to be adapted to make them operational, and (ii) how each framework measured sanitation sustainability, which was done by assessing if a framework differentiated between systems with distinct outcomes and if it provided a threshold for sustainability. To help understsand the influence of each framework's data processing method on the results, each framework's results were translated into ranks for each real system from first (best, most sustainable system) to twelfth (worst, least sustainable system) (Figure S1). The quantitative results from TechSelect and CIA, which used expert weightings and single-score aggregation methods, already ranked each of the twelve real systems. The other frameworks' results were semi-quantitative and qualitative, so ranks were assigned assuming equal weights between indicators. For SEI and TAF, the system with the most positive and the least negative indicator scores was ranked first. For UNICEF and CDC/ARC, systems were ranked within each indicator, then the sum of the indicator ranks was used to rank the systems.

Finally, for a broader understanding of how sustainability is measured, the complete set of indicators from all six frameworks were evaluated to determine common indicators, unique indicators, and indicator comprehensiveness. Indicators were categorized (Table 2) to help identify the different topics covered by each framework. Most frameworks categorized their indicators using the three pillars of sustainability (i.e., social, economic, and environmental). If a framework used sub-categories, they were consolidated into one of the three pillars based on theoretical understanding and typical categorizations used by sustainability frameworks[3,7,59,60] and meta-analyses.[2,61–63] (e.g., institutional indicators were categorized as social; technical indicators were categorized as environmental).

## Results & Discussion

### Sustainability Measurement Approaches and Topics

There were a total of 111 indicators used by the six frameworks. The most common indicators were *Reliability* and *Acceptability/Appropriateness,* which were included in all six frameworks; *Complexity*, included in five; *Investment Costs*, included in four; and *O&M Costs,* included in three.

When considering the three broad sustainability categories, environmental indicators were the most common (63 out of 111 total), followed by social indicators (36), and economic indicators (12) (Table S3).

From the 111 indicators, 25 main topics were identified (e.g., reliability, use, legal) (Table 2). Of these, four were covered in only one of the six frameworks: Replicability, Material Use, Compatibility with Existing System, Water Infrastructure. For the other topics, frameworks usually proposed different indicators to measure the same topic. For example, five frameworks included the topic of system performance. Two used global measurements, or indicators whose impacts are based on total supply chain resource use and emissions: TAF measured the *Potential for Negative Impacts or Benefits for Natural Resources on a Larger Scale*; TechSelect measured global *Eutrophication Potential*. The other three frameworks used local measurements: CDC/ARC suggested a generic *Water Quality Results* measurement; SEI used *Discharge* levels of biochemical oxygen demand, nitrogen, and phosphorous; and CIA used *Percent Removal* of organic matter, nitrogen, phosphorous, and total suspended solids. While the last two indicators measure similar pollutants, the measurements are different because percent removal does not assure a certain water quality, such that systems with the same final water quality can have very different indicator values since the removal is based on influent wastewater.

Usually, a topic would be more comprehensively evaluated by using multiple indicators (i.e., measurements). For example, the topic of water reuse could be better measured by the SEI and CIA frameworks; specifically by using both frameworks' *Potential for Water Reuse* indicators, where the SEI indicator measures quality ( "potential of technologies to achieve an effluent with enough quality to be reused") and the CIA indicator measures quantity ("percent of the consumption of the system"). This approach is used by UNICEF; it used multiple indicators to evaluate an ODF program's breadth and impacts (e.g., *Quality of Triggering Process* and *Quality of ODF Verification Process*). Overall, the differences between frameworks can lead to different conclusions for a given sustainability category, topic, and even indicator, so there is a need to ensure that frameworks' data collection approaches provide a complete and comprehensive evaluation.

**Table 2.** Summary of main indicator topics included in the selected sanitation sustainability assessment frameworks (individual indicators are listed in Table S2).

| Indicator | | | Framework | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sustainability Categories | Sustainability Sub-categories* | Main Topics | TechSelect | CIA | SEI | TAF | UNICEF | CDC/ ARC |
| Economic | Economic | Investment Costs | x | x | x | | | x |
| | | O&M Costs | x | x | x | | | |
| | | Capacity to Pay/Affordability | | | x | x | x | |
| | | Willingness to Pay | | | x | | x | |
| | | Other System Benefits | | x | x | x | | |
| Environmental | Health | Health & Hygiene | | | x | x | x | |
| | Environmental | Odors | | x | x | | | |
| | | System Performance | x | x | x | x | | x |
| | | Global Warming | x | | x | | | |
| | | Energy Use | | x | x | | | |
| | | Land Use | x | x | x | | | |
| | | Material Use | | | x | | | |
| | | Water Infrastructure | | | | | | x |
| | Technical | Reliability | x | x | x | x | x | x |
| | | Design Life | x | | x | | | x |
| | | Maintenance | | | | | x | x |
| | | Complexity | x | x | x | x | x | |
| | | Flexibility | x | | x | | | |
| | | Replicability | | | x | | | |
| | | Compatibility with Existing System | | | x | | | |
| Social | Social | Use | | | | | x | x |
| | | Appropriateness/Acceptability/Satisfaction | x | x | x | x | x | x |
| | | Education/Behavior Change | x | | x | x | | |
| | Institutional | External Support/Resources | | | | x | x | x |
| | | Legal | | | x | x | | |

**Reliability* and *Complexity* were categorized as social by CIA; *Willingness to Pay* was categorized as social by SEI; *Potential for Reuse* was categorized as environmental and *Local Development* as social by CIA and SEI; *Odors* was categorized as social by CIA. TechSelect, UNICEF, and CDC/ARC frameworks did not explicitly categorize their indicators, so category was based on the most common category used by the other frameworks and from Balkema et al. (2002).

## Framework Application and Adaptation

When the six frameworks were applied to the 12 existing cases, one-third of the 111 indicators needed adaptations due to lack of clear definitions (Table S4). Four frameworks required adaptations for nearly 50 percent of their indicators. This high level of adaptation was mainly due to the frameworks' use of generic scales without definitions (e.g., a generic three-level scale of low, medium, and high). Only one framework, TAF, required no adaptation because the framework included lengthy appendices with complete indicator definitions, measurement questions, and evaluation methods. Within the frameworks' indicator sustainability sub-categories, technical indicators required the most adaptation (76%), followed by social (55%), institutional (44%), health (43%), economic (33%), and environmental (26%) (Table S5). The relatively low level of adaptation for economic and environmental indicators was expected since these sustainability categories have been the most studied aspects of sustainability[2,6,59] and have well-established and widely accepted measurement methods.[64,65] The specificity of technical indicators could be improved by drawing from extensive monitoring and evaluation processes.[7,66,67] For example, Jacimovic and Bostoen (2017) propose five well-defined technical indicators to monitor humanitarian WASH interventions and to align these measurements with WASH humanitarian sector (i.e., Sphere) standards.[7] Overall, frameworks would benefit from increased specificity, such as providing more comprehensive and clear definitions for each indicator and including specific measurement (i.e., scoring) scales (e.g., definition of what "low" vs. "high" means for each indicator).

Results from the framework ranking (Figure S1) show that the two failed cases (Cases 12 and 17) were ranked last and second to last for nearly all frameworks; the exception was TechSelect, which gave a rank of seventh to one of the failed systems. For the ten successful cases, though, the six frameworks produced extremely varied results (Figure S1). For example, Case 13 ranged from a ranking of first (CDC/ARC) to eleventh (TechSelect). The varying results between frameworks is mostly due to indicator disparity and ambiguity, which is influenced by the disconnect between the constructs underlying each indicator and what is being measured. For example, the Joint Monitoring Program's definition of basic sanitation ("population using improved sanitation facilities, which are not shared")[1] is an indicator (i.e., a measurement of a particular construct) instead of a construct (e.g. "the minimum level of household sanitation service that delivers adequate privacy, dignity, and public health protection to users"). This disconnect is an issue because there has been agreement on the construct's definition of basic sanitation but disagreement on the indicators.[68–71] If frameworks are not based on unified definitions of sustainable sanitation constructs, then disagreement on which indicators should be used is likely.

Similarly, there was a wide range of rankings between frameworks for the successful systems likely because each framework defined and measured sanitation sustainability differently (Table S6). While some frameworks defined the construct of sustainability, these definitions often were not specific to sanitation, yet all of the frameworks' indicators were specific to sanitation. Therefore, there was a lack of agreement between the sustainability definition and how it was measured. For example, UNICEF relied on the Brundtland Commission's definition where "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs".[72] UNICEF's framework, however, lacked a means to measure future generation's needs specific to sanitation; its indicators focused on current sanitation system users, especially the system's impact on users' health and open defecation, and did not include a measure of the sanitation system's ability to meet broader or longer-term sustainable development goals.[36] Similarly, TechSelect's indicators did not adequately measure the framework's sustainability construct. TechSelect defined sustainable technology broadly as "a strategy that enables men and women to rise out of poverty and increase their economic situation by meeting their basic needs, through developing their own skills and capabilities while making use of their available resources in an environmentally friendly manner."[42] TechSelect's indicators focused primarily on environmental resources and immediate economic costs but lacked measures of poverty, skills development, and basic needs.

The other three frameworks (SEI, CIA, and TAF) used sustainability definitions and indicators that were sanitation-specific; this specificity may explain why these frameworks' indicators seemed more aligned with their sustainability constructs. For example, SEI and CIA adopted the same sustainable sanitation technology definition of a "technology that does not threaten the quantity and quality of resources and has the lowest costs with respect to the physical, socio-cultural and economic environments".[73] Both frameworks proposed at least one indicator to measure each of the main tenets of their sustainability definition. For example, SEI's indicators included measures of *Material Use* (quantity of resources), *Global Warming* (quality of resources), *System Performance* (physical), *Acceptance* (socio-cultural), and *O&M Costs* (economic).[33] TAF's definition was "the applicability of technologies, and of successful introduction, sustainable use, and the operation of technologies providing lasting services".[39] TAF's indicators measured each of its definitions' sustainability components such as *Demand for the Technology* (sustainable use) and *Sector Capacity for Validation, Introduction of Technologies, and Follow Up* (successful introduction).

Even when a there was alignment between the sustainability definition and the indicators, no framework provided adequate guidance to determine when a sanitation system met the goals of its sustainability construct due to unclear definitions and/or indicators that did not match the definitions. For example, CDC/ARC defined sustainability as "the long-term effectiveness of water and sanitation infrastructure", but it was unclear what "long-term effectiveness" meant and how the indicators proposed would measure this concept (no indicator had a time dimension). Overall, there is a need for frameworks to have a clear and measurable sustainability definition so that the most appropriate indicators can be used.[74,75] To help improve sustainability definitions and provide clear goals for achieving universal sanitation access, there should be a unified definition of sanitation sustainability.[28,29] Based on this evaluation of sustainability frameworks, a suggested unified definition of sustainable sanitation is a system that provides long-term functional, safe, and acceptable sanitation services while also minimizing negative social, economic, and environmental impacts.

There were 32 indicators that consistently scored successful systems as more sustainable than failed system (Table S7). Those indicators were related to levels of system use, maintenance, and performance as well as external support/resources and acceptability, which have also been previously found to be essential drivers of sanitation success.[5,52] The other indicators did not consistently differentiate between successful and failed systems. For example, for UNICEF's *Affordability* indicator, failed Cases 17 and 12 were scored as more sustainable than multiple successful cases, with a rank of fourth and tenth, respectively (Table S8); the failed systems were "more sustainable" because they had minimal to no costs associated with them. Similarly, for SEI's *Material Use* indicator, both failed cases used relatively fewer materials than SEI's 0 alternative and than six successful cases (Table S9), so the failed cases again appeared more sustainable for this single indicator. Frameworks need to consider ways to avoid suggesting that systems requiring minimal resources, because they are providing minimal services, are sustainable.

One approach would be to consider the impact of both individual and combined (i.e., sets of) indicators. Most existing sanitation sustainability assessment frameworks already include multiple indicators to avoid this issue. However, sanitation frameworks could further improve on sustainability measurements by identifying a universal set of comprehensive indicators. For example, four frameworks did not include an indicator to measure functionality of the sanitation infrastructure over its design life. Universal indicators have been identified in other sectors. For example, the food security sector adopted universal indicators, which improved their ability to measure, understand, and respond to food insecurity globally, enabling more effective humanitarian aid and policies.[74] Similar efforts are underway to identify universal water insecurity indicators.[75] A sector-wide effort to identify a core set of sanitation indicators could help align sustainability definitions and measurements as well as the sector's understanding of its coverage, impacts, effectiveness, and critical focus areas.

Another approach is to have flexibility in indicators to allow for context-specific preferences and information since context-specific differences could explain why some indicators were unable to consistently differentiate between the successful and failed cases. This is particularly important because some indicator measurements cannot be universal. For example, all six frameworks proposed some social indicators that are posited to be universal (e.g., *Odors, Visual Impacts, Noise, Convenience*), but the importance of these has been shown to vary by context.[25,76] Research demonstrates that priorities are context-specific[76,77] and that some communities value different aspects far more than topics specified in some frameworks (e.g., *Privacy* and *Low Cost* versus *Odors* and *Noise*).[25] Therefore, indicators that have not been proven to be universal and/or do not consistently differentiate between successful and failed systems should allow for context-specific adaptations. For example, frameworks could provide a set of possible social indicators to select from based on context or could choose a measurement approach that inherently includes this contextual adaptation, such as the *Addressed Sanitation Priorities Protocol*,[25] which evaluates how well sanitation systems address important, context-specific priorities.

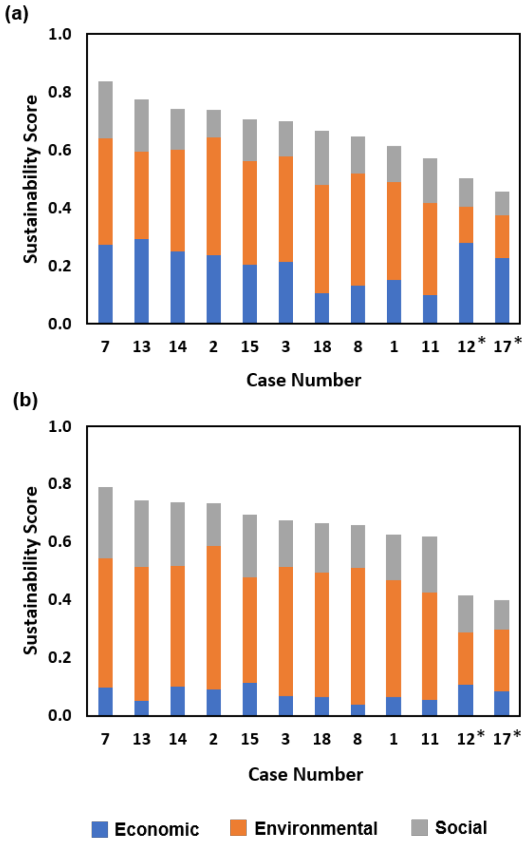

**Figure 1.** Comparison of CIA results using the CIA expert weightings (a) and equal weightings (b) for this framework's single-score aggregation approach. * denotes failed systems; all other systems were successful.

A third approach is to consider weights between indicators. For instance, the single-score aggregation frameworks (CIA and TechSelect) weighted indicators using expert opinions.[44,54] For CIA, the ten successful cases had higher scores than the two failed cases; however, there was less than a 1% difference between the "worst" successful case score and the "best" failed case score (Figure 1a), making it difficult to determine which systems were unsustainable. When the expert weights were replaced with equal weights across indicators, the score difference between the "worst" successful case and the "best" failed increased to 33%, which presented a clearer distinction between the 12 cases evaluated (Figure 1b). Similarly, TechSelect did not have a clear differentiation between successful and failed cases when using its expert weights, andthe ranking of cases was more accurate w hen the expert weights were replaced with equal weights across all indicators (Figure S2).

These results demonstrate that expert weights may not always be appropriate, particularly when there is a lack of consensus in the sanitation sector about the use of weighted approaches due to their potential to be misleading or prone to bias, and that weights may need to be context-specific (e.g., determined by local stakeholders instead of, or in addition to, expert weightings). If expert weightings are used, frameworks should seek to align their weighting schemes in pursuit of universally agreed upon weights that are developed using multiple experts since a limited number of experts (usually n<20) often results in weak expert consensus[28] and weightings that are highly sensitive.[28,29] For example, the comprehensive and long-established method to calculate disability adjusted life years (DALYS) uses universal, expert-derived weights that also incorporate local and social factors such as local air quality and gender.[78,79] Sanitation framework weights could emulate the DALYS model of expert weights that account for context-specific information to help reconcile the desired universality of indicators with the need for context-specific adaptations.

Many frameworks do not use weights, though, because they do not use quantitative data or aggregate indicator data. For these frameworks, the user may need to determine and use an aggregation method to attempt to differentiate between sustainable and unsustainable systems. TAF and SEI were both semi-quantitative frameworks that compare sanitation alternatives by scoring each indicator on a relative basis and displaying results in a summary table (Tables 3 and S9). These frameworks, instead of providing a single-score aggregation method, emphasized that sustainability is context-specific and suggested interpreting the results in partnership with local stakeholders. When these frameworks' results were aggregated by the authors (by assuming equal weightings of indicators and subtracting the total number of negative indicator scores from the sum of the positive and neutral indicator scores), both frameworks differentiated between the successful and failed cases. Therefore, weights between indicators can still be an important consideration for frameworks that do not aggregate data.

**Table 3.** Summary of the framework TAF's results, which used relative comparison to score each indicator.[†]

| Indicator Sub-category | Indicator | Case Number | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **18** | **11** | **13** | **7** | **15** | **14** | **8** | **2** | **3** | **1** | **12*** | **17*** |
| **Social** | Demand for the technology (user) | + | + | 0 | + | + | + | 0 | + | + | - | - | - |
| | Need for promotion and market research (producer) | + | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | - |
| | Need for behavior change and social marketing (regulator/investor) | + | + | + | + | + | + | 0 | 0 | + | 0 | - | - |
| **Economic** | Affordability (user) | + | + | + | + | + | 0 | 0 | 0 | 0 | 0 | - | - |
| | Profitability (producer) | + | + | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | - |
| | Supportive financial mechanisms (regulator/investor) | + | + | + | + | + | 0 | + | 0 | 0 | + | - | - |
| **Environmental** | Potential for benefits or negative impacts (user) | + | + | + | + | 0 | + | + | 0 | 0 | 0 | - | - |
| | Potential for local production of product or spares (producer) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Potential for negative impacts or benefits for natural resources on larger scale (regulator/investor) | + | + | + | 0 | 0 | + | 0 | + | 0 | 0 | - | - |
| **Institutional** | Legal structures for management of technology & accountability (users) | + | + | + | + | + | + | + | + | + | + | - | - |
| | Legal regulation and requirements for registration of producers (producer) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Alignment with national strategies and validation procedures (regulator/investor) | + | + | + | + | + | 0 | + | 0 | 0 | 0 | - | - |
| **Capacity** | Skillset of user or operator to manage technology (user) | + | + | + | + | + | + | + | + | + | + | - | - |
| | Level of technical and business skills needed (producer) | + | + | + | + | + | + | + | 0 | 0 | 0 | - | - |
| | Sector capacity for validation, introduction of technologies, and follow up (regulator/investor) | + | + | + | + | + | 0 | + | + | + | + | - | - |
| **Technical** | Reliability of technology and user satisfaction (user) | + | + | + | + | + | + | + | + | + | + | - | - |
| | Viable supply chains for product, spares, and services (producer) | + | + | + | + | + | + | + | + | + | + | - | - |
| | Support mechanisms for upscaling technology (regulator/investor) | + | + | + | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | - |

[†] Note: + = high value, neutral or positive, supportive characteristics; 0 = potential impact, could become critical, needs follow up; - = low value, negative, critical, hindering characteristics. * denotes failed systems; all other systems were successful.

UNICEF and CDC/ARC were intended for monitoring a single WASH project and did not definitively reflect which cases were successful or failed. However, each's individual indicators highlighted differences between cases (Tables S8 and S10) that could be used to identify improvements to an existing system. For example, CDC/ARC identified systems with no infrastructure maintenance committee (Cases 12 and 17) and systems that had committees with maintenance challenges (Cases 1, 2, 3, and 14). Since having a highly active committee to maintain WASH infrastructure is important,[52] stakeholders could use this information to strengthen committees' maintenance preparedness, such as by discussing how to improve sanitation fee collection and saving funds in a bank account.[58] Improvements to an existing system are also supported when indicators have sustainable targets. For example, CDC/ARC had three indicators with a quantitative target: 100% *Sanitation Coverage*; 100% *Water Infrastructure Coverage;* and 75% *Hygiene Behavior Coverage.* UNICEF recognized 100% as the ideal target for all of its indicators but encouraged framework users to evaluate those targets to assure they were context-specific and realistic (e.g., based on national standards or implementing organization program goals).

## Framework Development and Use

The many existing sanitation sustainability assessment frameworks have different intended applications. It is likely that the wide differences in framework results (Figure S1) is partially due to this difference. To ensure that stakeholders select the most appropriate framework for their goals (e.g., using a planning framework like SEI for technology selection instead of post-implementation impact evaluation), frameworks should clearly state intended applications and limitations.

Usually the intended application is based on the sanitation project's phase (e.g., planning new or monitoring existing), which has a very large impact on the type, amount, and quality of data available. Some frameworks use theoretical values and others measure actual values. Theoretical values for indicator measurements are useful for comparing between technology alternatives in the planning phase, but they may not accurately characterize built infrastructure. For example, CIA measures *Odors* based on theoretical emission factors[80] but does not account for odor emissions when system designs vary from theoretical designs or are poorly performing. Also, frameworks and the types of data they use could be better differentiated. For example, "technology alternatives potential" could be used for frameworks intended for planning and that rely heavily on theoretical indicator measurements. "Baseline monitoring" could be used for frameworks that evaluate a single sanitation system's impacts or track a system's impacts over time. "Relative sustainability" could be used for frameworks that compare systems but do not quantify impacts, while "absolute sustainability" could be used for single-score aggregation frameworks that quantify and compare system impacts.

The data quality and availability issue is also reflected in the ways in which frameworks are developed and tested, which varied among the selected frameworks (Table 1). A common testing approach, used by three of the six selected frameworks, is to use hypothetical scenarios to demonstrate how a framework works and identify general technology characteristics. A main limitation of this approach is that data limitations (e.g., data collection challenges, undefined indicator measurements) are usually not encountered during framework testing. However, data limitations are common, especially in resource-limited contexts, so frameworks should use a testing approach that helps to identify the influence of these limitations (e.g., pilot-testing with real sanitation systems or contexts).

A major reason for the limited use of sustainability assessment frameworks is that many organizations lack the resources to conduct resource-intensive evaluations (e.g., with extensive data collection).[4,81] To make frameworks more accessible, they should, where possible, use indicator measurements that are realistic and require minimal resources. For example, *Willingness to Pay* is typically measured using the widely-accepted but highly time-intensive[82] contingent valuation method.[83] Investigating if less resource-intensive indicators can also effectively measure *Willingness to Pay*, such as *Acceptance,* as called for by WHO and UNICEF,[1] can improve framework accessibility and use. Another way to reduce a framework's resource demands could be proposing well-defined alternatives (e.g., qualitative scales) to complex measurement methods, such as the qualitative scale used by SEI to measure *Risk of Infection* instead of a health risk assessment (which are beyond most implementing organizations' regular capabilities[84]). Also, frameworks should eliminate redundant indicators to minimize data collection and analysis requirements. For example, measuring both *Material Use* and *Global Warming Potential* may not be necessary since the former is used to calculate the latter (e.g., both midpoint and endpoint impacts are not always needed), and indicator dependencies could exaggerate a system's impacts.

Frameworks that include less resource-intensive and non-redundant indicators will be easier for organizations with resource limitations to use. To help achieve this, frameworks could use a different testing approach, such as pilot testing of the indicators and data processing methods with real, implemented systems. Pilot testing was used by the other three selected frameworks (Table 1) and better allows developers to identify potential roadblocks for data collection and to determine whether indicators accurately capture intended results. Two frameworks, UNICEF and TAF, revised indicator metrics after pilot testing and have since continued to update the frameworks' guidance manuals.[36,55]

Overall, the sanitation sector as a whole should also seek consensus on a unified sanitation sustainability definition and a baseline set of universal indicators. Effective frameworks require well-defined, comprehensive indicators and context-specific weightings They also need to provide adequate guidance for stakeholders to select a framework, understand and evaluate indicators, process the data, interpret the results, and determine whether systems do (or could) meet minimum thresholds for sanitation sustainability. These recommended improvements to sanitation sustainable assessment frameworks could increase the use and effectiveness of existing and future frameworks, which could lead to better sanitation decision-making and in turn, improved public and environmental health, economic viability, and sanitation use and acceptance.

## Supporting Information

Details of the methods and additional results tables and figures.

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