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Policy Analysis

Re-Envisioning Sanitation As a Human-Derived Resource System

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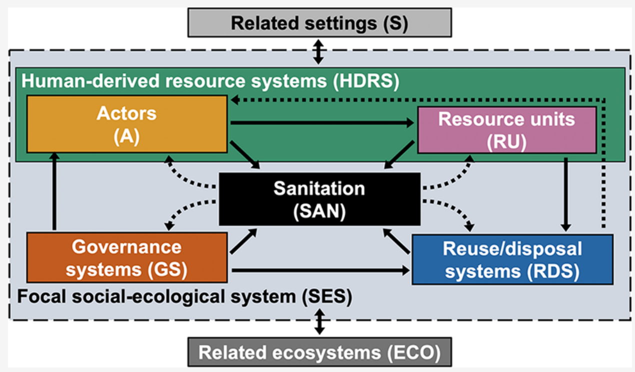
ABSTRACT: Sanitation remains a global challenge, both in terms of access to toilet facilities and resource intensity (e.g., energy consumption) of waste treatment. Overcoming barriers to universal sanitation coverage and sustainable resource management requires approaches that manage bodily excreta within coupled human and natural systems. In recent years, numerous analytical methods have been developed to understand cross-disciplinary constraints, opportunities, and trade-offs around sanitation and resource recovery. However, without a shared language or conceptual framework, efforts from individual disciplines or geographic contexts may remain isolated, preventing the accumulation of generalized knowledge. Here, we develop a version of the social-ecological systems framework modified for the specific characteristics of bodily excreta. This framework offers a shared vision for sanitation as a human-derived resource system, where people are part of the resource cycle. Through sanitation technologies and management strategies, resources including water, organics, and nutrients accumulate, transform, and impact human experiences and natural environments. Within the framework, we establish a multitiered lexicon of variables, characterized by breadth and depth, to support harmonized understanding and development of models and analytical approaches. This framework's refinement and use will guide interdisciplinary study around sanitation to identify guiding principles for sanitation that advance sustainable development at the nature-society interface.



■ INTRODUCTION

Globally, over two billion people lack basic sanitation access, and even more use systems that do not safely manage human excreta.[1,2] Progress toward the Sustainable Development Goal (SDG) of universal sanitation coverage by 2030 remains limited: of 123 countries with <95% basic sanitation coverage, only 14 are on track for universal coverage.[1] In resource-limited communities characterized by poverty, poor infrastructure, and constrained access to food, water, and other basic needs, high failure rates plague sanitation systems, leading to increased environmental and human health risks.[3,4] Simultaneously, global agriculture continues to consume finite nutrient resources (e.g., phosphate rock) while large quantities of phosphorus and anthropogenically fixed reactive nitrogen are discharged to pollute aquatic environments.[5,6]

Recovering human-derived resources from sanitation (e.g., water, nutrients, organic matter from bodily excreta) has the potential to offset treatment costs, substitute for expensive or nonlocal inputs (e.g., synthetic fertilizers, polyhydroxyalkanoates), and improve resource access for populations facing financial or productivity constraints.[7−9] Recent research and policy efforts, particularly those associated with sustainable and circular economies, have promoted shifts from pollutant removal to resource-oriented management.[9−12] However, although technology options are rapidly expanding, multiple socioeconomic, environmental, and engineering challenges coconstrain sanitation-based resource recovery efforts (e.g., economic viability of recovery, market potential, and consumer acceptance of products).[9,13−16] Recognizing these challenges, sanitation research is becoming more interdisciplinary and incorporating broader stakeholder involvement. Consequently, many studies have developed and applied models, tools, and approaches linking sanitation with social, environmental, and resource systems, with the goal of examining multiple dimensions of sustainability and supporting decision-making.[14−31] Work in Mexico City, for example, linked social acceptance (through participatory scenario development) with environmental outcomes (through resource flow analysis) to

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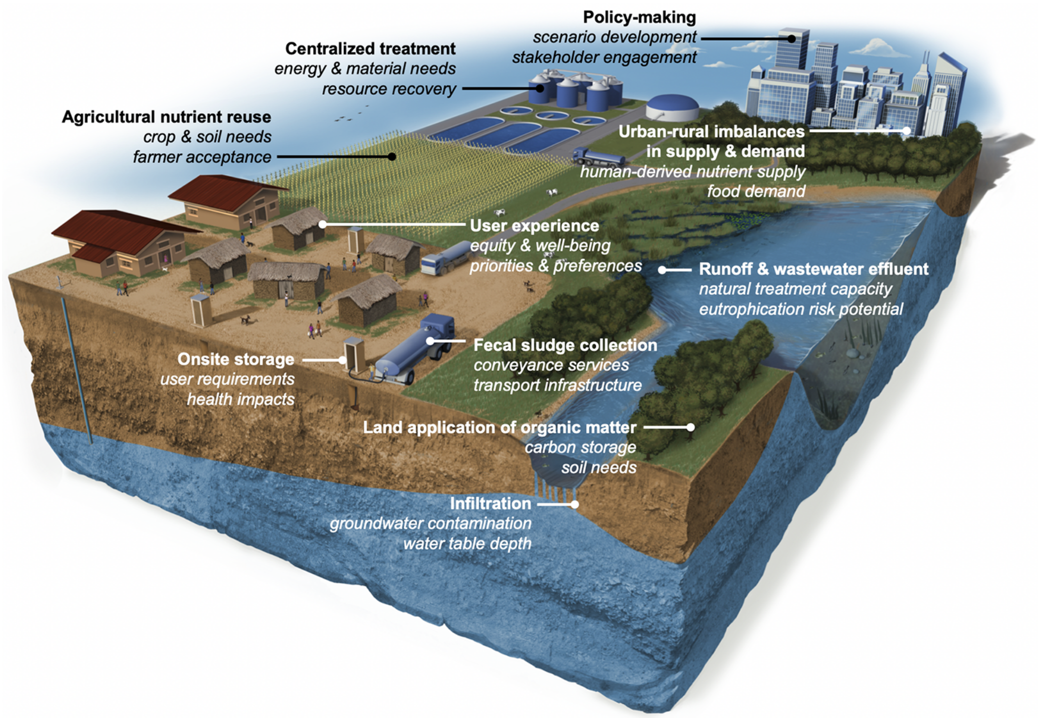

Figure 1. Illustrative components of human-derived resource systems. Sanitation can function as an interface connecting multiple aspects of social, ecological, and resource systems. These linkages can be positive, as in cases where resources (water, organics, nutrients) are recovered and recirculated toward beneficial uses, or negative, as in cases where disposal displaces resources, contaminating environments and degrading ecosystem services.

evaluate water and sanitation possibilities.[32] More generally, authors have used nutrient recovery to reframe sanitation as an overlooked component of food and farming systems.[10,33] Others have noted the importance of integrating economic, social, and engineering systems to ensure the effectiveness of natural wastewater treatment systems (e.g., constructed wetlands, lagoons), particularly concerning pathogen control and human health protection.[34] The phosphorus cycle has received particular attention,[35−39] and human-derived phosphorus recovery pathways were recently reviewed from an integrated social, ecological, and technical perspective.[40]

This accumulation of research has contributed to a more inclusive, holistic vision for sanitation. Yet many research and implementation efforts remain separated from other disciplinary perspectives or are designed for specific settings or technologies. Without a common set of variables to guide the development and application of models and tools—essentially, without a shared vision establishing an interdisciplinary vocabulary of sanitation-related factors and interactions—scholars may focus too narrowly on certain topics while overlooking other characteristics that can affect outcomes.[41−43]

Communicating across various perspectives can be challenging, particularly when terminology differs or when factors considered critical by some disciplines go unacknowledged by others. Consequently, new knowledge may remain isolated.[44,45] The plethora of existing and newly created tools, indicators, and indices might even engender confusion among sanitation actors, uncertain of which one(s) to apply in their situation.[46] For example, in an initiative incorporating sustainability into technical standards for nonsewered sanitation systems, expert consensus on which criteria to include was difficult to establish, due to the various technologies, assessment strategies, and definitions of sustainability that exist.[47,48] Effective standards require a common understanding and can support innovative solutions.[48] Developing a shared vision for sanitation and resource recovery—one that aspires to benefit society and the environment through contextually appropriate, integrated systems—will help to frame thinking and improve communication among diverse scholars and stakeholders.[43] Such a shared vision can support the development of models that advance suitable, place-based approaches supported by effective stakeholder engagement and interdisciplinary understanding of broader social and environmental contexts.

Sanitation represents an interface between society and nature. It is an integrated system that can be both beneficial, through human-derived resources recirculated toward positive use, and detrimental, when improper disposal degrades natural resources (Figure 1). Beyond sanitation, efforts to analyze coupled human and natural systems have been underway for over a decade.[46,49,50] Scholars have developed a generalized social-ecological systems (SES) framework,[41,44,51,52] which emerged from studying governance of common-pool resources (e.g., forests, irrigation systems, fish stocks)[53] and has been tested in many contexts.[42,54−60] The SES framework has offered a common set of relevant variables when studying resource management, classifying these variables within a structure of interrelated subsystems.[41,44] It has also aided in identifying factors that affect whether users will self-organize to manage resource systems.[44] Similar analyses could provide insight into sustained functioning of sanitation systems. The SES framework can be modified to guide a re-envisioning of sanitation as a human-derived resource system, providing a structured understanding of sanitation's role as an interface connecting various social, ecological, and resource systems (Figure 1). The resulting framework can support research

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elucidating sanitation's multidimensional relationships with multiscalar conditions (e.g., government policies, community priorities, household-level practices),[16,19,20,26,30,61] thereby promoting collaborative movement toward more sustainable resource cycles.[62]

Accordingly, our objective is to advance a shared vision for sanitation as a human-derived resource system—in which people are part of the resource cycle—thereby supporting transitions toward sustainable resource metabolisms across social-ecological systems. Starting from relevant literature and the SES framework, we develop a sanitation SES (S-SES) framework that reflects the unique characteristics of sanitation and resource recovery. We present the framework's overall structure, consisting of high-level subsystems related to topics such as governance, actor groups, and reuse opportunities. We then expand upon each subsystem, discussing how numerous variables may influence optimal design, decision-making, and management of sanitation systems across spatial, temporal, and disciplinary dimensions. These multitiered structures of variables represent a shared lexicon that can standardize terminology, provide a foundation for various types of models, and translate specialized disciplinary expertise to facilitate interdisciplinary communication, fostering a balance of breadth and depth as we work toward a generalized understanding of sustainable sanitation. The S-SES framework offers opportunities to think about sanitation in new ways and develop insight gleaned from integrated perspectives, which we illustrate by describing how the framework shaped our own understanding of the changing nature of human-derived resources. Moving forward, we offer the S-SES framework as a foundation for specialized and interdisciplinary study among researchers, decision-makers, and stakeholders. Over time, its refinement and use will build evidence across contexts, scales, and disciplines to advance knowledge and establish core guiding principles for sustainable human-derived resource systems.

Critical to the inspiration and development of this framework was a parallel study evaluating sanitation alternatives in an informal settlement in Kampala, Uganda.[63] As we will describe, this contextual study provided insight into some of the key factors associated with sanitation in resource-limited urban settings, factors we have incorporated into the S-SES framework. Further, that study combined various concepts from the framework (e.g., sanitation as a modular service chain, user satisfaction levels, and life cycle economics and environmental impacts) to analyze sanitation alternatives across multiple dimensions.[63] Consequently, it is the first example of how this framework can reciprocally guide and be influenced by contextual research.

A SOCIAL-ECOLOGICAL SYSTEMS FRAMEWORK FOR HUMAN-DERIVED RESOURCES

Our Definition of a Framework. Following the approach of the SES community, we define frameworks as being categorically distinct from models.[52] Models examine specific aspects within a broader topic to evaluate outcomes, often requiring simplifying assumptions to control variations in other system elements. In contrast, a framework acts as scaffolding to support model development across a breadth of topic areas, providing an overarching vision and vocabulary of variables from which models can draw.[52,53] A framework does not determine precise model structure, operationalize links between components, define how to parametrize variables, or decide which variables to include in specific applications.

Instead, a framework defines a conceptual way of thinking about a multifaceted system. It helps to standardize terminology used in more specific models and encourages awareness of other system features external to such models, enabling more effective communication and knowledge accumulation across disciplines that employ different assumptions, tools, and evidence. Models may focus on sections of a framework to study subsets of variables, while the overarching framework structure points toward how to communicate findings and build evidence across fields and settings.

Moving forward in reciprocal dialogue, model development can suggest how to refine a framework, providing greater clarity and additional information regarding key variable classes.[52] For example, our parallel study in Kampala, Uganda confirmed the importance of including variables in the S-SES framework that are related to existing urban sanitation and transport infrastructure, as well as users' current satisfaction with sanitation services.[63] Inversely, integrating concepts from existing literature to develop our framework suggested strategies we could apply to our contextual work.[63] In Kampala, we modeled sanitation systems as modular service chains of storage, collection, conveyance, treatment, and reuse processes,[22,31] and we evaluated alternatives with respect to resource, economic, and environmental outcomes using techniques such as techno-economic analysis, material flow analysis, and life cycle assessment.[20,26] That analysis generated findings that readily map onto the structure of our conceptual framework.

The General SES Framework. The general SES framework was developed to study common-pool resources such as forests or fisheries. These resources are characterized by high subtractability (also called "rivalry": use diminishes resource quantity or quality) and low excludability (it is difficult to bar actors from using the resource).[56] While this combination of traits may create short-term gains that incentivize overconsumption by individual actors, appropriate governance institutions or collective action can transcend these challenges.[41,53] In fact, SES literature has revealed that effective management is possible (and may be more successful in at least some cases) without externally imposed governmental regulations or market incentives.[53,64]

Accordingly, the SES framework (Supporting Information (SI) Figure S1) reflects the fact that sustainable management of these systems must consider a mixture of social and ecological aspects.[41,44,52,55,56] Five first-tier variables represent core subsystems interacting within the overall SES: (i) Resource systems, representing the overarching area, ecological zone, or system that contains and supports the resource of interest (e.g., forests, lakes, grazing areas); (ii) Resource units, which are parts of the resource system used to create value (e.g., trees, fish, cattle); (iii) Actors, including individuals or groups who use, collect, transform, manage, or own resource units (e.g., loggers, fishers, farmers); (iv) Governance systems, defining rules under which actors operate (e.g., regulations, monitoring regimes); and (v) Focal action situations, representing interactions, decisions, and outcomes that occur across these subsystems and generate feedbacks.[44,52,55] Two additional subsystems represent the broader social-ecological context: (vi) Related social, economic, and political settings; and (vii) Related ecosystems.[44]

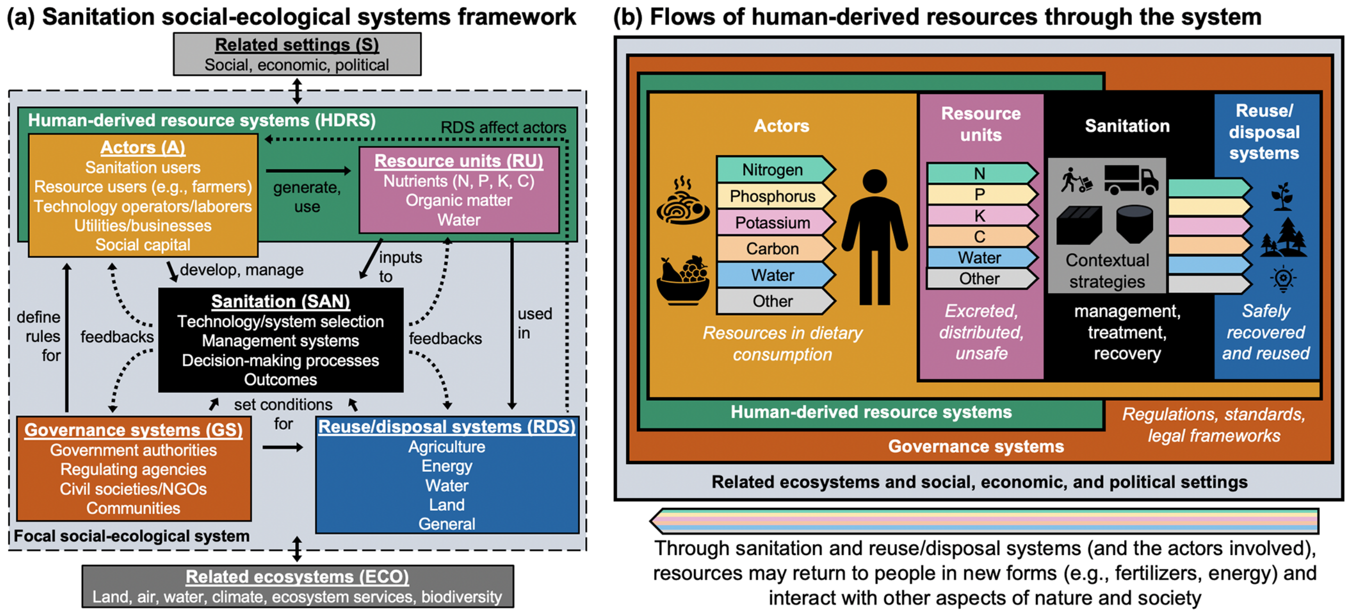

Figure 2. The sanitation social-ecological systems (S-SES) framework. (a) The diagram shows the seven first-tier variables (also called core subsystems; e.g., sanitation, actors, related ecosystems) of the S-SES framework and includes distinct categories (second-tier variables; e.g., technology selection, sanitation users, water) within each core subsystem. The framework structure extends beyond the first and second tiers to provide additional layers of detail as needed; structured lists of third- and fourth-tier variables can be found in SI Tables S1−S7. (b) Flows of human-derived resources through the core subsystems of the S-SES framework suggest how the safety and accessibility of resources may change as they move through various stages. Appropriate management, treatment, and recovery strategies, implemented by actors operating within a policy and regulatory environment defined by governance institutions, can increase safety and minimize risks associated with recovered resources. However, these processes may introduce constraints on access related to technology availability, economic resources, and knowledge of sanitation and hygiene.

These seven subsystems, dividing the overall system into broad, interactive components, represent the first tier of variables in a multitiered structure. Each subsystem is disaggregated into distinct categories and properties through additional tiers of nested variables (e.g., SI Tables S1−S7). For example, second-tier variables within the resource units subsystem describe properties such as a resource's economic value, distribution, or mobility.[41,44] This structure helps to conceptualize a complex whole and facilitate research, classification, and communication at varying degrees of specificity.[41,44,52] Most studies concerning the general SES framework have established several second-tier variables, defining broadly relevant characteristics of each first-tier component.[41,44,52] A few studies have proposed general third-tier variables (e.g., differentiating between spatial and temporal distribution of resource availability),[52] further expanded deeper tiers in specific contexts (e.g., benthic fisheries),[54] or built out specialized components for illustrative purposes.[57] Since its inception, continued development of the SES framework has expanded its application to contexts beyond common-pool resource systems, including some with distinct technological components (e.g., energy infrastructure).[55,56]

The Sanitation SES (S-SES) Framework for Human-Derived Resource Systems. Human-derived resources are similar to common-pool resources in that they are subtractable (i.e., consumption diminishes supply), and individuals have nonexcludable access to their own excreta. However, resources are only safely available when appropriate sanitation technologies are employed (imparting a degree of excludability). Disposal of bodily excreta may consume, degrade, or enhance other natural resources (e.g., improved soils through organic product application). Given these distinct traits, and the fact that people are integrated into human-derived resource cycles through excretion, we modified the configuration of the general SES framework's first-tier variables (i.e., its highest conceptual level).

Three key modifications (SI Figure S1) produced the first-tier structure of the S-SES framework (Figure 2). First, rather than including the resource system separately, we define the human-derived resource system as an overarching component linking two first-tier variables: actors (some but not necessarily all of whom contribute resources by using the sanitation systems under consideration) and resource units (e.g., nutrients, organics, and water managed in sanitation systems). This approach reflects previous work related to the resource recovery potential of sanitation,[7,36,65−67] in which an individual's diet is linked with bodily excretion and recovery of resources through sanitation. However, we do not fully merge actors and resource units into a single variable. They are linked but remain distinct, because, for example, people are active participants with at least some agency over their behavior within the system (unlike water or nutrients).

Second, a new first-tier variable—reuse/disposal systems—has been added, directly linking sanitation with broader resource cycles. Reuse/disposal systems offer platforms for human-derived resources to return to actors in different forms (e.g., energy, soil amendments, concentrated nutrient products such as struvite), or, through their disposal, to consume resources or alter their quality in related ecosystems. These interactions may facilitate important system feedbacks. For example, agricultural nutrient reuse can increase food availability or cropping options, potentially altering sanitation users' dietary intake over time. Regulations and legal

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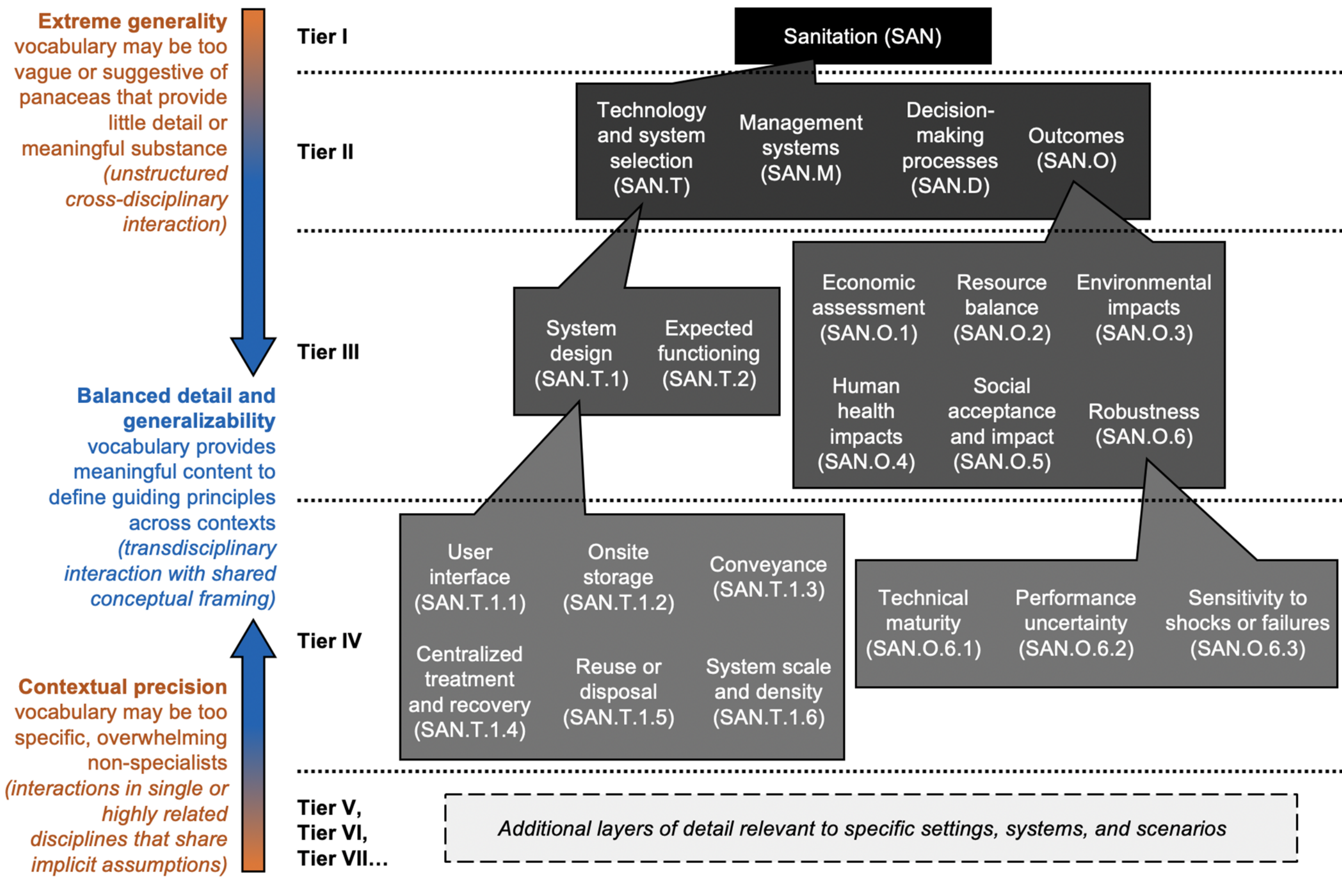

Figure 3. An illustration of the framework's multitiered structure, using the sanitation subsystem as an example. The sanitation subsystem is expanded into four second-tier variables. Of these, we further expand technology and system selection (SAN.T) and outcomes (SAN.O) to show nested third-tier variables (the other two second-tier variables also contain lower tiers not pictured here). Two third-tier variables are then expanded to the fourth tier. For all core subsystems, full structured lists showing four tiers of variables can be found in SI Tables S1−S7. Additional variables, in levels beyond the fourth tier, can offer even greater levels of system detail and contextual depth. As they are likely to become increasingly context-dependent, we have not specified variables beyond the fourth tier. On the left, we show how a tiered structure is important when developing a shared vision and lexicon. Many studies may benefit from high levels of generality or precision, but finding a balance is important for effective interdisciplinary communication. Otherwise, researchers may remain trapped within existing boundaries by keeping other topic areas too vague or being too dependent on implicit disciplinary assumptions. A multitiered conceptual framing can help researchers speak to others with different perspectives, balancing these two extremes at midlevel tiers. Researchers can delve deeper to identify key aspects of ancillary topics, or translate specialized results to identify generalizable knowledge, typologies, and guiding principles.

frameworks defined by governance systems also impact reuse or disposal activities (e.g., quality standards for nutrient products, restrictions on land where open defecation occurs), ideally (but not always) helping to mitigate risks for groups including sanitation users, sanitation workers, farmers, consumers, and external actors impacted by system externalities (spillover effects).

Finally, the central first-tier variable—sanitation—was adapted from the general framework's "focal action situations" to focus on decisions and outcomes around sanitation system design and management. This keystone represents a critical point of interaction across the other first-tier variables and is particularly large, complex, and multifaceted. The S-SES framework's multitiered structure (described below) can help to disaggregate the many categories of decisions and outcomes associated with sanitation systems and identify the most critical aspects in a given context. Various nested attributes of actors, governance structures, resource units, and reuse/disposal options, as well as broader socioeconomic and ecological characteristics, affect the viability of sanitation and recovery opportunities, while sanitation strategies create feedbacks influencing characteristics and possibilities across the entire system.

A SHARED LEXICON OF VARIABLES WITHIN A MULTITIERED STRUCTURE

Balancing Generality and Precision Using Tiered Structures. After establishing the S-SES framework's overarching structure, we expanded each first-tier variable to include multiple levels of additional variables (Figure 3 exemplifies this multitiered structure within the sanitation subsystem; SI Tables S1−S7 provide full structured lists). Establishing a multitiered structure helps avoid two extremes deriving from the need to balance global and local needs: excessive generality (offering little meaningful content) and excessive precision (offering little applicability beyond specific circumstances or perspectives).[52] Along with their importance for model development, these issues relate to interdisciplinary communication. Each person brings a distinct lens, shaped by disciplinary vocabularies, conventions, and conceptions of reality, which can create conflicting starting points for conducting and describing research.[68−73] Absent a shared conceptual vision, interactions may create confusion as disciplinary concepts are explored in ways that are too vague or too specific, overwhelming participants in a labyrinth of unfamiliar terminology.[69] Individuals may then revert to disciplinary biases, maintaining a fragmented status quo.[69,71] Alternatively, some disciplines and perspectives inherently provide insights that are more cross-cutting and less classifiable into single domains. For example, technopolitical approaches reveal how use, regulation, or modification of a technology (e.g., a water meter) can represent human action in the political sphere; essentially, the technology itself becomes political terrain for protest, subversion, control, or advancement of a particular philosophy.[64,74] An overarching framework can integrate such perspectives to elucidate relationships across domains, helping others to understand these connections and push beyond conventional boundaries.

The shared vision provided by a multitiered conceptual framework can support understanding of variables, relationships, and terminology at different levels,[41,44,52,75] while providing guidance on how to balance generality and precision in an interdisciplinary context (Figure 3). For example, an engineer may broadly state that "social issues" or "governance systems" hinder successful sanitation. These phrases, corresponding to first- or second-tier S-SES variables, may not provide sufficient detail to generate meaningful solutions. Alternatively, a study may present detailed findings concerning the treatment of specific pollutants using a certain technology, which are important but may be too context-specific to scale up or may rely too heavily on discipline-specific terminology. They would likely fall beyond the S-SES framework's fourth tier, and generalizability would be difficult from an interdisciplinary perspective. In both cases, the framework could pull researchers toward a balance of detail and generality, delving more deeply into important high-level concepts and showing how specialized findings become critical for determining overall outcomes. Specific results may differ across cases (due to contextual rules, cultural outlooks, or physical attributes), but they can reveal broader shared traits that point toward pathways for success.[53] These efforts are necessary to support interdisciplinary collaboration and arrive at evidence-based guiding principles for sustainability applicable across a range of contexts. We propose this balance is likely found in the vocabulary of the third and fourth tiers (Figure 3), where teams can define broad but detailed typologies of barriers, opportunities, and strategies, providing insights that speak to general trends and context-specific challenges.

Tiered Structures of Variables. We used insights from our work in Kampala, Uganda[63] and the general SES framework's tiered structure[41,44,52,54−57] to guide the selection and placement of variables within the S-SES framework. We reviewed literature to identify and classify relevant variables included or implied in modeling analyses, decision support tools, or other approaches. Our goal was to develop a standardized structure representing multiple layers of detail, which the research community can refine and use to develop contextually appropriate and broadly consistent models, thereby facilitating knowledge accumulation across studies. Accordingly, the framework can help researchers translate study- and discipline-specific findings so that others can learn from, use, and build on them.

Generally, we define second-tier variables as distinct categories or common issues within a first-tier variable. For example, nutrients, water, and organic matter represent distinct resource unit categories, while social capital represents a topic relevant for multiple actor types. Third- and fourth-tier variables represent nested attributes that provide further detail, while remaining general enough to describe sanitation systems across various scales, technologies, and management strategies. Even the fourth-tier variables we include are not sufficiently detailed to fully characterize individual systems. Future studies using this framework (or advancing it for specific disciplines, contexts, or technologies) can further define more specialized variables appropriate for their (and similar) applications, while employing existing variables to help translate their findings and point toward generalizable principles.

Below, we summarize variables nested within each of the framework's subsystems. We focus particularly on third- and fourth-tier variables, which may be most useful for interdisciplinary translation of findings as studies accumulate evidence toward guiding principles for sustainable sanitation.

Sanitation. The central sanitation subsystem contains the largest number of nested variables, encompassing design and management of sanitation facilities, decision-making processes, and multidimensional outcomes (Figure 3; SI Table S1). The S-SES framework conceptualizes a full sanitation system as an integrated service chain of multiple components (user interface, onsite storage/treatment, conveyance, centralized treatment/recovery, reuse/disposal), each of which must be considered in relation to its complementary processes.[22,31] Especially in settings such as urban informal settlements, safe excreta management depends upon the performance and connectivity of multiple processes (e.g., latrine containment, sludge emptying, centralized treatment).[63] In Kampala, Uganda, 60% of bodily excreta was estimated to be unsafely managed in 2014, primarily due to unsafe emptying or latrine abandonment.[76]

Design and decision-making processes themselves may contribute to a sanitation system's continued functioning. Participatory processes engaging diverse stakeholders and municipal authorities can increase likelihood of success by identifying community priorities, developing and visualizing alternative scenarios, and navigating trade-offs involving different groups, sustainability criteria, or value categories.[3,4,14,16,28,30,77,78] They can also help build consensus and empathy across actors through decision support techniques (e.g., the analytic hierarchy process, which compares alternatives relative to preselected criteria).[16,46] Evaluating system outcomes to support design and engagement efforts may reveal trade-offs or synergies across sustainability dimensions. We found such effects in our contextual modeling in Kampala, Uganda, where one scenario's economic and environmental outcomes were better than the existing system, while the most expensive scenario also had the lowest greenhouse gas emissions.[63] Broadly, sustainability dimensions can include economics (e.g., life cycle costs, resource value), environmental impacts (e.g., aquatic pollution, climate change potential), resource efficiency (e.g., materials, energy), human health (e.g., disease risks, nutrition), social acceptability (e.g., regulatory compliance, employment opportunities, equity), and technological robustness (e.g., sensitivity to shocks).[26,79−90] Many established quantitative approaches used to elucidate outcomes of sanitation systems (e.g., life cycle assessment, techno-economic analysis, quantitative risk assessment)[26,91−95] connect directly with this portion of the framework.

Resource Units. The resource units subsystem focuses on potential supplies of recoverable human-derived resources (e.g., nutrients, organic matter, water; SI Table S2). Generation rates of resources—and their availability for recovery and reuse—depend upon local diets, sanitation system configurations, and recovery technologies.[7,8,36] If recovered, their forms will influence contextual suitability and market value. For example, agricultural irrigation with appropriately treated wastewater may be suitable if cropland is close at hand, whereas nutrient-dense products such as struvite may be superior when nutrient demands are more distant (due to transport requirements).[65,96,97] Prices, sources, regulations, externalities, and availability regarding existing alternatives (e.g., imported fertilizers) or items needed for resource recovery (e.g., magnesium for struvite precipitation) will also affect human-derived products' viability and value.[7,98,99]

Reuse/Disposal Systems. Parallel to recovery product types and supplies defined by the resource unit subsystem, reuse and disposal systems consider the roles and demands for resources in agriculture, energy, and water systems (SI Table S3). Reuse possibilities will be affected by factors including regional cropping systems and dietary preferences, conventional household cooking or heating fuels, the balance between existing water use and available water resources, and stakeholder decisions (e.g., fertilizer budgets, application timing). Reuse may be especially advantageous in areas where resources are scarce or costly to produce, for example, when seawater desalination provides drinking water, or when fertilizer access is limited and application of human-derived nutrients may improve crop yields.[9,36] Additionally, this portion of the framework explores how reuse or disposal impacts available natural resource supplies and services, creating direct connections with related ecosystems. Environmental impacts include reductions in natural water quality due to untreated wastewater discharge or agricultural runoff, or greenhouse gas emissions related to Haber-Bosch nitrogen fixation or nitrous oxide release following nutrient application.[100,101] Across reuse/disposal systems, general factors related to the proximity of resource supply and demand, spatial and temporal demand variations, storage and transport capacities of built infrastructure or natural systems, and actors' ability to acquire and maintain equipment for reuse/disposal will affect the feasibility of potential management strategies.[65,96]

Actors. Various actors may interact with sanitation systems (SI Table S4), including entrepreneurs, operators, utilities, and resource users (e.g., farmers). Additionally, sanitation system users are critical to the concept of human-derived resource systems. Without them, resource flows would not occur. Broadly, involving various stakeholder groups in planning is a critical element of pathways toward sanitation success.[3,4] Through their deep knowledge of local systems, stakeholders' participation in generating and evaluating models can help to overcome validation concerns associated with complex systems modeling (although it is important to recognize the potential for asymmetric information and influence across stakeholder groups).[46] Accordingly, ensuring that communities are represented holistically is critical. The priorities, preferences, perceptions, cultural norms, and relationships within human systems will impact effective strategies for collective management and possibilities for resource recovery.[28,102] Similarly, spatial and demographic distributions of sanitation system users and resource users (which may overlap) will impact sanitation system scale, facility location, and the proximity of resource supply and demand.[65,103] For sanitation users in particular, dietary intake will influence resource excretion and potential recovery quantities.[7,36,104] Externalities may also affect people outside of the system boundary. For example, practices such as open defecation or untreated wastewater discharge can impair stream quality for downstream populations. Across all actors, social capital and the properties of social networks may affect levels of trust, willingness to interact with various groups and institutions, motivations for interaction, and the prospects for building consensus.[16,105,106]

Governance Systems. Sanitation and resource systems must be compatible with the regulating and enforcement mechanisms of governing authorities, the collective management and property rights arrangements of communities, and the decision-making, monitoring, accountability, and knowledge-sharing frameworks of implementing organizations (SI Table S5).[41,44,53] These governance structures define the rules (e.g., regulations, standards) that actors are expected to follow.

Contextual sanitation strategies will also help to determine what particular regulatory mechanisms are necessary. If pit latrines are common, for example, standards are needed for their construction and decommissioning, while centralized wastewater treatment plants operate under effluent discharge requirements. Recently, standards developed for nonsewered sanitation systems included aspirational statements related to sustainability (e.g., cultural appropriateness, life cycle affordability), although experts did not reach consensus on specific principles and indicators to include.[47,48] This result may reflect inherent difficulties associated with defining and quantifying sustainability, and the existence of many different sustainability assessment tools. Establishing a shared vision of sustainable sanitation is critical to the development of sustainability standards, which can then support innovative approaches.[48] When exploring the dynamics of how individuals or stakeholder groups may respond to new standards or policy changes, approaches such as agent-based modeling can be useful in predicting the emergence of larger-scale economic, political, environmental, or technological outcomes (e.g., land use change, technology diffusion).[46] However, such simulation techniques should not be assumed to provide conclusive evidence of real-world behavior, as agent-based models can be highly sensitive to large numbers of uncertain parameters and cannot fully capture diverse decision-making processes within human systems.[107]

Related Social, Economic, and Political Settings. All subsystems described previously exist within a broader social, economic, and political context (SI Table S6). Social characteristics surrounding demographic trends, cultural norms, and institutions for human capital (e.g., education and skills training, health care) will affect actors' distributions, preferences, priorities, and capacities.[30,108,109] Similarly, factors such as existing forms of government and national or regional stability define the political setting. These attributes may impact workable governance frameworks, collaborative opportunities, jurisdictional boundaries or conflicts, economic volatility, barriers to infrastructure development, and the migration, displacement, or marginalization of local populations.[106,110,111] They may also influence human interactions with technologies, which can represent particular political viewpoints or development philosophies.[64,74] Political circumstances will interact with economic conditions related to international trade and investment, local access to savings and

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credit institutions, resource and raw material availability, and inertia of existing infrastructure investments. In turn, this economic environment can influence local sanitation and resource markets, willingness to take on risks associated with infrastructure transitions, and the interest rates and taxes associated with sanitation investments and business opportunities.[61,85,112−115]

Related Ecosystems. Sanitation and resource systems also interact closely with local and global ecosystems (SI Table S7). Local climate may impact the viability of treatment systems, especially when employing temperature-dependent biological processes or inactivating pathogens via solar radiation.[116,117] Land use patterns and soil characteristics such as pH, organic carbon, and nutrient retention capacity may affect the appropriateness of recovery or disposal strategies.[65,66] Additionally, land applying recovered nutrients may enhance ecosystem services[67] and reduce eutrophication caused by aquatic nutrient discharge (although agricultural runoff and gaseous emissions may still create adverse impacts).[18] Alternatively, some treatment processes—including conventional activated sludge—are energy-intensive, while the degradation of bodily excreta can release potent greenhouse gases under certain conditions (e.g., methane in anaerobic environments, nitrous oxide during nitrification/denitrification).[82,89,116]

Together, these subsystems of the S-SES framework enumerate a wide-ranging (though not exhaustive) taxonomy of attributes and parameters that may be considered when designing, modeling, or evaluating sanitation systems and their roles in context-specific scenarios. A study's selection of relevant variables, relationships, and modeling techniques will depend upon its hypotheses, objectives, and methods. The overarching goal in developing this framework is to better equip researchers to engage with one another and the broader literature by raising awareness of diverse factors that cross disciplinary boundaries, factors that (understandably) may be external to some study designs but remain important in influencing sanitation sustainability. The framework also points toward types of information that may be most useful in accumulating an evidence base to define generalizable trends, system typologies, and guiding principles. We suggest that relating key findings to third- and fourth-tier variables and showing their impacts on overall system outcomes may be especially constructive, providing a balance of generality and precision. Over time, we expect that the framework—and the lexicon of variables it contains—will be refined and expanded, becoming a more effective guide for research and action toward sustainable sanitation systems.

■ THE CHANGING NATURE OF HUMAN-DERIVED RESOURCES

In addition to providing a foundation for contextual studies, a conceptual framework can also influence thinking about a topic more broadly. A lens integrating various disciplines and concepts may generate new insights for understanding sanitation. In this section, we describe an example of how re-envisioning sanitation as a human-derived resource system affected our own thinking. As we considered the resources in sanitation systems in light of concepts from fields such as economics, natural resource management, political science, and health, a synthesis began to emerge focused on how different management strategies and reuse pathways might affect the nature of human-derived resources (Figure 4). Specifically, human-derived resources may represent different categories of goods, distinguished by their excludability and subtractability (also called "rivalry").[56] These characteristics can have direct relevance for policy and collective action. For example, private goods (high excludability, high rivalry) may function successfully under free market conditions, while effective management of public goods (low excludability, low rivalry) may require government subsidies, community-led monitoring and sanctioning, or shared social capital and norms surrounding issues such as conservation.[41,44,53,64]

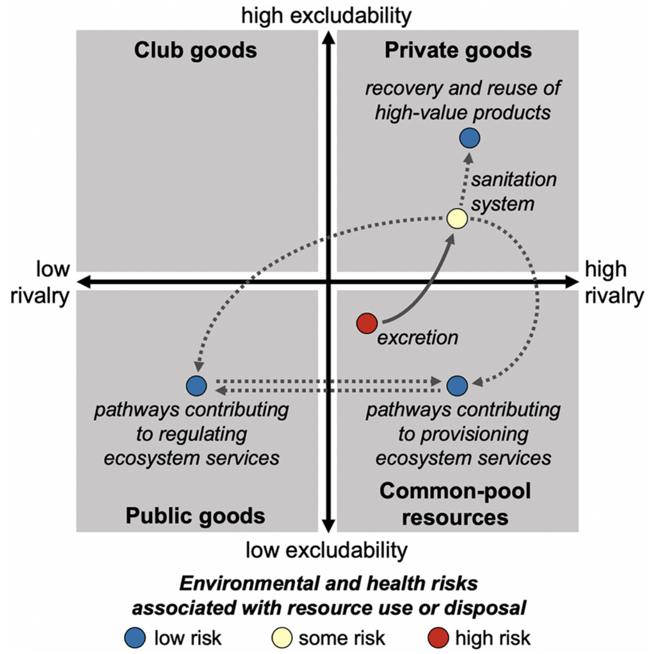

Figure 4. The changing nature of human-derived resources. This figure illustrates how a conceptual framework can provide an integrated lens across disciplines and concepts, suggesting new ways of understanding sanitation that can then be studied further. Here, we show a synthesis that arose organically as we developed the framework and allowed it to influence our own thinking. Integrating ideas from fields including economics, natural resources, and health, we considered how different types of reuse pathways change the nature of human-derived resources. Specifically, we consider the types of goods these resources represent, as defined by their excludability (i.e., the degree to which actors can be barred from using the resource) and rivalry (also called subtractability; i.e., the degree to which resource use diminishes the quantity or quality of the remaining supply). Sanitation systems manage and treat bodily excreta to reduce risks associated with reuse or disposal, but limited access to technologies, economic resources, and knowledge regarding appropriate strategies can function to exclude vulnerable populations. Advanced recovery processes that generate more expensive, higher-value products (private goods) may further increase excludability. Alternatively, other pathways (for example, those connected with ecosystem services) may generate common-pool resources (e.g., provisioning of forests or fish stocks) or public goods (e.g., regulation of water or air quality). In the interest of completeness, the figure includes club goods—the fourth general category of goods, defined by high excludability but low rivalry—although this category does not enter directly into our discussion of human-derived resources.

Upon excretion, human-derived resources initially appear similar to common-pool resources (i.e., low excludability but high subtractability),[56] with each person having access to a limited supply (the quantity that individual excretes). However, using resources immediately after excretion would

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entail considerable health risks, and appropriate management and treatment strategies are needed before safe recovery and reuse. Therefore, sanitation systems enter the picture, beginning to transform the nature of human-derived resources. These systems often collect materials from multiple individuals (with centralized approaches imparting a greater degree of aggregation), but limited access to sanitation technologies and limited knowledge of appropriate management strategies increase excludability, particularly for vulnerable populations. Moreover, improper disposal at this stage (e.g., through untreated wastewater discharge causing eutrophication) may degrade other environmental resources such as freshwater quality or fish populations.

With more appropriate strategies, human-derived resources may transition toward private goods (high excludability and subtractability),[56] especially if sanitation systems are operated by private companies and recovered products are sold on the market. Economic circumstances determine one's ability to access these resources. Recovery of higher-value products (e.g., concentrated nutrient products such as struvite) may further increase excludability, as these processes often require advanced technologies imparting additional costs that may reduce affordability for lower-income actors.[99] However, decentralized sanitation systems may distribute access across more economically diverse groups, particularly in rural areas with low availability of conventional resources (e.g., limited access to imported fertilizers due to high transaction and transportation costs).[118]

Alternative pathways, such as those directing human-derived resources to support ecosystem services, may effect transformations toward less excludable forms and encourage synergistic interactions between nature and society.[67] For example, land application of organic matter stores carbon in soils (rather than emitting it into the atmosphere), contributing to climate regulation. This pathway represents a conversion toward public goods (low excludability, low subtractability),[56] benefiting society as a whole. Traditional market-based economics may not incentivize transformations toward lower excludability, but they can be encouraged through mechanisms such as government subsidies, institutions for collective action that foster more equitable resource access and conservation values,[53,64] or financing schemes around payments for ecosystem services.[67,119,120]

Although these three potential end points for human-derived resources (private goods, common-pool resources, public goods) may appear distinct (Figure 4), they are not necessarily mutually exclusive. Innovative strategies for managing human-derived resources may simultaneously capitalize on multiple pathways. However, processes may operate over unequal time scales, as private goods provide more immediate value, while ecological public goods may take longer to realize.[121] For example, advanced nutrient recovery processes can generate marketable agricultural products (private goods), while also contributing to better management of nutrient cycles. In particular, existing phosphorus cycles represent largely linear flows from finite phosphate rock supplies to aquatic contamination.[122] If recovered nutrients are no longer displaced into aquatic systems through wastewater discharge, potential for eutrophication and its adverse environmental impacts[123] may decrease over time, contributing to public goods such as the aesthetic, recreational, cultural, and ecological value of natural waters.[124] The cleaner water in fisheries may also promote healthier, more numerous fish populations (a common-pool resource).[123,124]

In effect, innovative and contextually appropriate management pathways may transform human-derived resources from potentially unsafe, destructive materials (whose disposal degrades ecosystems and consumes goods) into more constructive forms supporting mutually beneficial interactions between nature and society (and enhancing supplies of nonexcludable goods). Generally, studying the changing nature of human-derived resources theoretically and in specific contexts can lead to better understanding of how and when to direct recoverable resources toward different forms, and how to evaluate impacts across disparate temporal scales.[121] More broadly, this example illustrates that working with the S-SES framework to explore human-derived resource systems can reveal new insights, which might otherwise remain hidden in the absence of an interdisciplinary vision.

■ ADVANCING THE FRONTIERS OF SANITATION RESEARCH

In the SES community, the creation of a systematic framework has spurred research that increases understanding of effective resource management and has provided a structure to accumulate knowledge across disciplines and contexts.[42,52,54−56,59,60,77,106,125−128] We envision the S-SES framework as potentially performing similar functions, supporting interdisciplinary thinking and communication to define a frontier for sanitation research and development. Persistent gaps and frequent failures associated with improving sanitation access[1,3,4] indicate a complexity requiring multiple perspectives and approaches that fully appreciate and address the relationships linking human, technological, and environmental systems. The framework provides a foundation for navigating complexity and building generalizable knowledge of sustainable sanitation systems.[3,4,30]

Despite the numerous variables involved (SI Tables S1−S7), the present framework does not identify certain parameters as most or least important. Rather, it offers a uniform starting point that avoids weighting some factors more heavily than others, embracing multiple perspectives, analytical approaches, and types of findings.[48] The framework can offer insight into what elements are explicitly analyzed in a research study, illuminate limitations and features outside the study's scope, and help integrate evidence from diverse contexts and approaches to elucidate overarching trends, critical factors, and generalizable relationships.[43]

For example, results from our study of sanitation alternatives in Kampala, Uganda (which inspired, and was also influenced by, the development of the S-SES framework) revealed that the most suitable path forward will depend on local priorities.[63] Replacing existing pit latrines and conveyance systems with container-based sanitation would greatly increase resource recovery potential and generate the lowest greenhouse gas emissions of any option considered, but it would also increase system costs. Users' satisfaction with toilet facilities may increase or decrease, depending upon whether container collection can be implemented successfully and in a way that creates employment opportunities for residents. In contrast, continuing to use pit latrines while replacing existing centralized treatment with anaerobic technologies could improve both economic and environmental outcomes, with essentially no change in users' experience of latrine facilities (including difficulties with emptying).[63] Considering the topic

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areas of the S-SES framework not explored in this study, it would benefit from complementary research into the political feasibility and implications of these alternative technological trajectories within human systems. A technopolitical approach may reveal underlying political philosophies represented by these options and illuminate the ways in which users, sanitation workers, and regulators might interact with technologies.[64,74] That insight may lead back to more detailed technical analysis of a preferred alternative, moving sanitation forward in this setting, while similar progressions in other contexts could begin to suggest broader patterns (and particular influential factors) that contribute to sustainable sanitation in informal settlements.

Moving forward, scholars may iteratively advance and operationalize the framework in at least two interconnected ways: (i) using the framework to guide analysis and reporting in diverse contexts to accumulate knowledge and support decision-making; and (ii) expanding or refining the framework structure to better reflect theoretical developments concerning the nature of sanitation systems and human-derived resources. Ultimately, the S-SES framework can advance new ways of thinking about human-derived resource systems and identify guiding principles that inform sustainable development at the interface of nature and society.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c03318.

> A figure presenting the general social-ecological systems (SES) framework and the modifications that produced the sanitation SES framework for human-derived resource systems; Structured, multitiered lists of variables contained within each first-tier variable of the sanitation social-ecological systems framework(PDF)

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