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Possibilities for changing to resource recovery in Kampala's on-site sanitation regime

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ABSTRACT

Pressure is growing to develop innovative decentralized sanitation systems that protect public health and recover resources. This study evaluates the opportunities for niche technologies focusing on nutrient resource recovery to enter the market in Greater Kampala, Uganda. It applies methodology from sustainability transition studies in a novel way to provide new insights into possibilities for change in the on-site sanitation sector. The study 1) characterizes the existing socio-technical regime for on-site sanitation, 2) identify stress points in the regime and 3) possible advantages for the niches. Assessment of the regime covers technology, epistemic practice, sector values, organisational modes, policy and financing. The niches include urine diversion toilets, on-site resource recovery, and container-based models. The on-site sanitation regime is under performing and the niches all offer advantages for improved service and resource use. However, it will be difficult for the niches to break into a sector in which epistemic practice, organisational modes and financing are heavily dominated by the sewage regime. Recommendations for creating a more open environment for innovation are provided for specific stakeholders.

1. Introduction

Rapid urbanization and growing recognition of the health and environmental consequences of poor sanitation have led to specific targets within the Sustainable Development Goals (SDGs) that call for "sanitation for all" (SDG 6). At the same time, the world is facing critical resource shortages and ecosystem collapse from mismanagement of nutrient cycles (Steffen et al., 2015). Yet these challenges do not have to contradict each other. It has been estimated that sanitation and wastewater services geared towards resource recovery and recycling can positively influence 14 of the 17 SDGs (Andersson et al., 2016).

In most low and middle income countries, on-site systems are the dominant service. African cities are currently experiencing an extraordinary urban transformation, making the region one of the fastest urbanization zones in the world (Xu et al., 2019), with corresponding problems of slum growth and lack of public services as a result. On the positive side, rapidly changing urban areas also offer opportunities for redesigning and rethinking traditional structures for sanitation management. This is true for the Greater Kampala Metropolitan area, where less than 2% of the population are currently connected to a conventional wastewater treatment (McConville et al., 2019).

Purely based on volume and proportion of people serviced, the opportunities for improving services and upscaling resource recovery in a city like Kampala are greatest in the on-site service regime. In Kampala Metropolitan area, only 56% of human waste is estimated to be safely treated (McConville et al., 2019), with a low level of resource recovery today. Pressure is growing to develop innovative decentralized systems that both protect public health and recover resource flows, while still allowing for rapid service expansion to underserved populations (Larsen et al. 2013). A number of niche innovations are developing in this area, including on-site techniques for source-separation and resource recovery, container-based toilets and innovative management schemes for resource recovery. This article explores the opportunities for increasing use of these services.

However, implementation of sanitation services is more than just the application of technology. It is connected with social norms, institutionalized management structures and access to knowledge and resources. Sanitation solutions need to be recognized as socio-technical systems that includes users, organisations and technology acting within society (Geels and Schot 2007). Indeed, there are multiple studies

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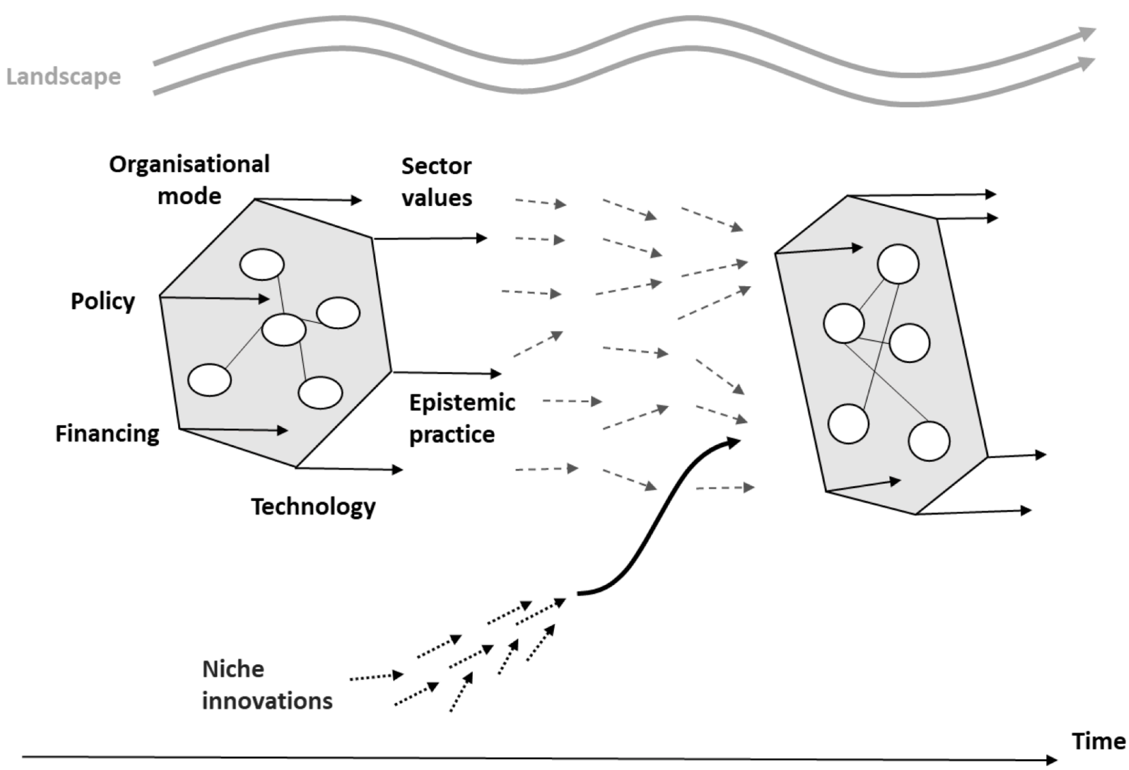

Fig. 1. The multi-level perspective on socio-technical transitions highlights the influence of landscape, niche innovations and internal regime stress on changes within the socio-technical regime (adapted from Geels 2002).

showing that up-scaling of innovation within the sanitation sector is hindered by issues with organisational management, acceptance and technical norms (Cherunya et al., 2020; Lennartsson et al., 2019; McConville et al., 2017a). When seeking to understand opportunities for introducing innovations within these types of systems it is useful to use sustainability transitions frameworks, including the multi-level perspective (Geels 2002).

The aim of this study is to evaluate the potential for introducing nutrient recovery into the Greater Kampala sanitation sector from a transition perspective. We focus on nutrient recovery technologies that apply separation of wastewater fractions in the on-site sanitation regime. Specifically, we assess the existing sanitation situation (socio-technical regime) in order to understand its weaknesses, before assessing where innovative niches may offer advantages, and thus momentum for change. The study applies theory from sustainability transition in a novel way to illuminate the socio-technical dynamics of the on-site sanitation sector in Uganda. The study has set the following objectives: 1) characterize the existing socio-technical regime for on-site sanitation and 2) identify stress points in the regime and 3) possible advantages in the niches that may create opportunities for change to nutrient recovery systems.

2. Conceptual framework

2.1. Characteristics of socio-technical transitions

There is a growing research community focusing on understanding how complex socio-technical systems evolve and how we can transform these systems into more sustainable ones (Köhler et al., 2019; Markard et al., 2012). Transition studies use trans-disciplinary and multi-dimensional analysis to gain new perspectives and understandings that can help society move towards sustainability. Sustainability transition studies are often framed using the multi-level perspective (Geels 2002) in which changes in socio-technical systems are influenced by three levels: landscape, regime and niche (Fig. 1). The landscape consists of slow-changing trends, e.g. norms, economics and environmental conditions that influence the other levels. The central level is formed by the mainstream way of doing things, called the regime.

The regime is shaped by technical infrastructure, but also by deep norms and social rules that create a stability in the existing system (Geels 2011). Three dimensions shape the regime: cognitive, normative and regulative (Geels 2004). Cognitive rules are formed based on common knowledge and shared experience that define mental models of reality and influence how actors solve problems (Geels 2006). This study uses *technology* (Geels 2002) and *epistemic practice* (Eriksson and Lindberg 2016) as characteristics of the cognitive rules of the regime. The normative dimension is defined by shared values and norms that define the social appropriateness of actions within the regime. Here, we analyse the normative characteristic of *sector values* (McConville et al., 2017a) and role expectations within *organisational modes* (Fuenfschilling and Truffer 2014). The regulative dimension refers to formal rules and cost structures that regulate behaviour within the regime. In this study, we assess *policy* (Geels 2002) and *financing* (Fuenfschilling and Truffer 2014) structures as regulative characteristics of the regime. Inadequacies or inconsistencies within these characteristics can create stress within the regime (Geels 2005).

New development and radical innovations are called niches (Geels 2011). In order to succeed, the niche needs to be integrated into the regime, or destabilize the regime so that the innovation becomes the new norm (Geels and Schot 2007). The focus of this study is on niches that enable nutrient recovery.

2.2. Sanitation service regimes

A proper sanitation system should include a *containment* unit for human waste at the point of generation, *collection and transport* to a treatment facility to be safely *treated* before *end-use* of the resulting product. The entire process is known as the sanitation service chain. In this study, we also recognize that a sustainable service also requires appropriate planning before implementation of the sanitation chain.

Table 1
Overview of the niche technologies compared in this study.

Niche	Containment	Collection & transport	Treatment	Recyclable product	Existing versions of the niche	TRL level*	Guiding principles
1	Double-vault, urine diversion dry toilet (UDDT)	Regular urine collection. Faeces emptied when 2nd vault Is full. Urine & faeces transported to an eco-station.	Urine: storage Faeces: composted	• Liquid urine • Compost	Full-scale implementation in: Bolivia (Huasi, 2018) South Africa (Mkhize et al., 2017) Uganda (Tumwebaze et al., 2011)	9	- environment - health - water savings - production of fertilizer - provision of sanitary modules (including handwashing) - citizen participation
2	Double-vault, urine diversion dry toilet (UDDT)	Dry urine & faeces transported to an eco-station (*fewer transports due to reduced urine volume*).	Urine: alkaline-dehydration in toilet (Senecal et al., 2018; Simha et al., 2018). Faeces: sanitized with urea after composting (Nordin et al., 2009).	• Dried urine • Urea-enriched compost	Pilot versions in: Finland (Simha et al., 2020a) Sweden (Simha et al., 2020b)	6	- environment - health - water savings - production of fertilizer - provision of sanitary modules (including handwashing) - citizen participation
3	Blue Diversion Autarky toilet (Larsen et al., 2015) is a UDDT with on-site treatment of all waste, including the handwashing water.	Minimal	Urine: stabilized with hydrated lime and excess water evaporated (Randall et al., 2016). Faeces: hydrothermal oxidation (HTO), resulting in water & inorganic solids. Wash water: gravity-driven membrane filtration system combined with activated carbon filter and electrolysis (Nguyen et al., 2017).	• Dried urine • Mineral product from faeces • Disinfected water	Pilot versions in: South Africa & Switzerland (Eawag 2020)	Varies ** 4 - urine treatment 3 - faeces treatment 6 – water treatment	- safety & comfort (modular design) - handwashing - water recovery - pathogen inactivation - nutrient recovery
4	Container-based sanitation (CBS) units with urine-diverting squat plate.	The company services the toilets, including operational support and daily collection services.	Urine: infiltration into soil Faeces: Black Soldier Flies (BSF) composting followed by co-composting of frass with additional organic material.	• Insect-based animal feed • Compost	Full-scale implementation in: Kenya, Haiti, Peru, & India	9	- franchise networks - affordability - accessibility - comfort & convenience, - handwashing - safe treatment with valuable end-products

*Technological Readiness Level as defined by the (European Commission 2019)
**Personal communication, Kai Udert (EAWAG 2021).

Failure or misuse at any of the steps in the service chain can result in health risks and environmental degradation. In many cities around the world, there exist several parallel sanitation service chains, or service regimes, e.g. sewers, on-site and public toilets (van Welie et al., 2018).

In the Greater Kampala Metropolitan area, there are two predominate service regimes, the sewage regime and the on-site sanitation regime that manages faecal waste from on-site sanitation systems (McConville et al., 2019). Nearly 99% of the population in Greater Kampala is currently connected to the on-site or faecal sludge management regime. Even if plans to expand the sewer networks are achieved, at least 70% of the population will remain connected to on-site sanitation services in 2040 (Government of Uganda/NWSC 2015). Indeed, sanitation coverage in the on-site sanitation regime is increasing faster than sewer coverage. Just over 5 million urban dwellers in Uganda gained access to on-site sanitation from 2000 to 2020, compared to 0.1 million gaining connections to sewers during the same period (WHO/UNICEF n.d.). Coupled with a growing international trend towards non-sewered solutions (Hoffman et al. 2020), this study has chosen to focus on assessing the on-site sanitation regime and potential for innovative nutrient recovery niches within it.

2.3. *Nutrient resource-recovery niches*

This study includes four different niches that are designed for maximum capture of nutrients from human waste (Table 1). Source separating sanitation systems were chosen because numerous studies have highlighted the need for source control and source separation for safe recovery and reuse (Cordell et al., 2011; Larsen et al., 2009; McConville et al., 2017b). The niches represent various stages of development and differing levels of technical complexity and management structures. Note that these niches only manage human excreta and not greywater.

3. Material and methods

The methodology used in this analysis is based on the premise that opportunities for innovation and change are greatest when the existing regime is stressed (Geels and Schot 2007; de Haan and Rotmans 2011). The analysis assesses the state of the regime with respect to the six regime characteristics (see 2.1), with the aim to identify areas of internal inconsistency, inadequacy or other problems affecting sanitation service delivery. The innovation niches may have a competitive edge if they offer solutions that overcome these stresses.

Assessment of the existing sanitation regime is based on methodology developed by Fuenfschilling and Truffer (2014) and McConville et al. (2017a). However, we have further developed the methodology by adding specific assessment variables to each regime characteristic (Table A.1 in the Appendix) in order to understand the level of stress in the regime. In addition, the evaluation of each regime characteristic is specifically adapted to include the concept of multiple service regimes and the entire sanitation service chain.

Information to evaluate the regime and the niches within each dimension was collected from a variety of sources, including national statistics, national policy documents, literature, and semi-structured interviews of experts (Table A.1). The initial results from the regime analysis were validated with local stakeholders in 2018, including representatives from the municipality, utility, university, NGOs and aid organisations. The methodology for assessing each dimension is briefly explained below. Full details of the methods for evaluating for each dimension and assessment variable can be found in the supplementary material.

3.1. Technology

The physical structures that enable functioning of sanitation services, e.g. toilets, transportation, treatment plants. Performance assessment focuses on the degree to which they allow for safe recycling of nutrients from human excreta. Two variables were assessed; i) the degree to which human excreta is estimated to be safely managed in the regime and ii) adequacy of nutrient recovery in the regime. Safely managed excreta was visualized using a simplified Shit-Flow Diagram (SFD) based on data in the Kampala Sanitation Master Plan (Government of Uganda/NWSC 2015) and on assumptions in an existing and updated SFD for Kampala (Niwagaba, n.d.). Recovery of nutrients in the regime was analysed using a substance flow analysis, using available data from the regime and niches on recovery/losses. For the cases when no direct data was available, assumptions were made, extrapolated from related technologies/processes.

3.2. Epistemic practice

Epistemic practices are related to the knowledge that people use to frame reality and are characterized by knowledge production and learning (Eriksson and Lindberg 2016). The availability and content of knowledge related to sanitation that is taught in national universities can be seen as representative of the epistemic practice used by sanitation professionals active in the on-site regime in Kampala. Assessment of epistemic practice was based on content review of course curriculums for Bachelor and Masters programs related to bioprocessing, environmental science, civil engineering, water engineering and agricultural engineering from five Ugandan universities (section C in the supplementary material). Data analysis focused on the content and proportion of sanitation curriculum dedicated to on-site systems and resource recovery. Coding was performed in the qualitative data analysis software NViVo 11 and results validated during stakeholder interviews.

3.3. Organisational mode

The organisation mode of the regime includes the roles and responsibilities of actors involved in provision and access to services along the sanitation chain. These actors can be private households, utility, public-private partnerships, private firms, community (informal/formal), etc. Assessment was based on review of documents that describe institutional roles and responsibilities, triangulated with semi-structured stakeholder interviews and field observations. Roles and responsibilities of stakeholders for implementing and coordinating/monitoring was than mapped across the sanitation service chain in order to identify any possible gaps or overlaps/inconsistencies.

Table 2
Scoring of the potential for the niche innovations to enter the market in the on-site sanitation regime of Kampala, Uganda. In general, + means the niche has an advantage over the existing regime, 0 means the niche does not differ significantly from the current regime, - means the niche has a disadvantage compared to the current regime.

	Cognitive **Technology** *Adequacy of safely managing waste*	*Adequacy of nutrient recovery*	**Epistemic practice** *Adequacy of knowledge regarding systems*	*Normative* **Organisational mode** *Roles & organisational capacity in the service chain*	*Coordination between actors*	**Sector values** *Compatibility between sector values and niche principles*	*Regulative* **Policy** *Inconsistencies or contradictions in policy*	**Financing** *Adequacy of revenues to cover costs*	*Division of costs between stakeholders*
Current on-site sanitation regime	Only 55% of human excreta is safely managed.	Only about 1% of N and P can be recovered in the system today	More knowledge related to the sewage regime than on-site sanitation. Low level of knowledge regarding resource recovery	There are multiple actors covering all roles along the service chain. Private actors primarily do implementation, while public actors do monitoring and enforcement.	The diversity of actors involved in the service chain, particularly in end-use creates confusion and is indicative of weak organisational structures.	Sector values are dominated by providing access and investments and institutional aspects of regulation and governance. Health and environmental protection and gender equality are also valued highly.	The FS regime itself is battling for policy space with the sewage regime, which is dominating the policy environment. There are more documents in the beginning of the service chain.	Revenues do not cover capital or operating costs, with the exception of the SMEs (small and medium enterprises) collecting faecal sludge.	Households, majority of whom are financially weak actors, pay a majority of capital and operating costs of the system.
Niche 1: UDDT	+	+	0	–	0	0	0	0	–
Niche 2: Urine drying	+	+	–	–	0	0	0	0	–
Niche 3: Autarky	+	+	–	–	+	0	0	–	–
Niche 4: Container-based Sanitation	+	+	–	0	+	0	0	+	+

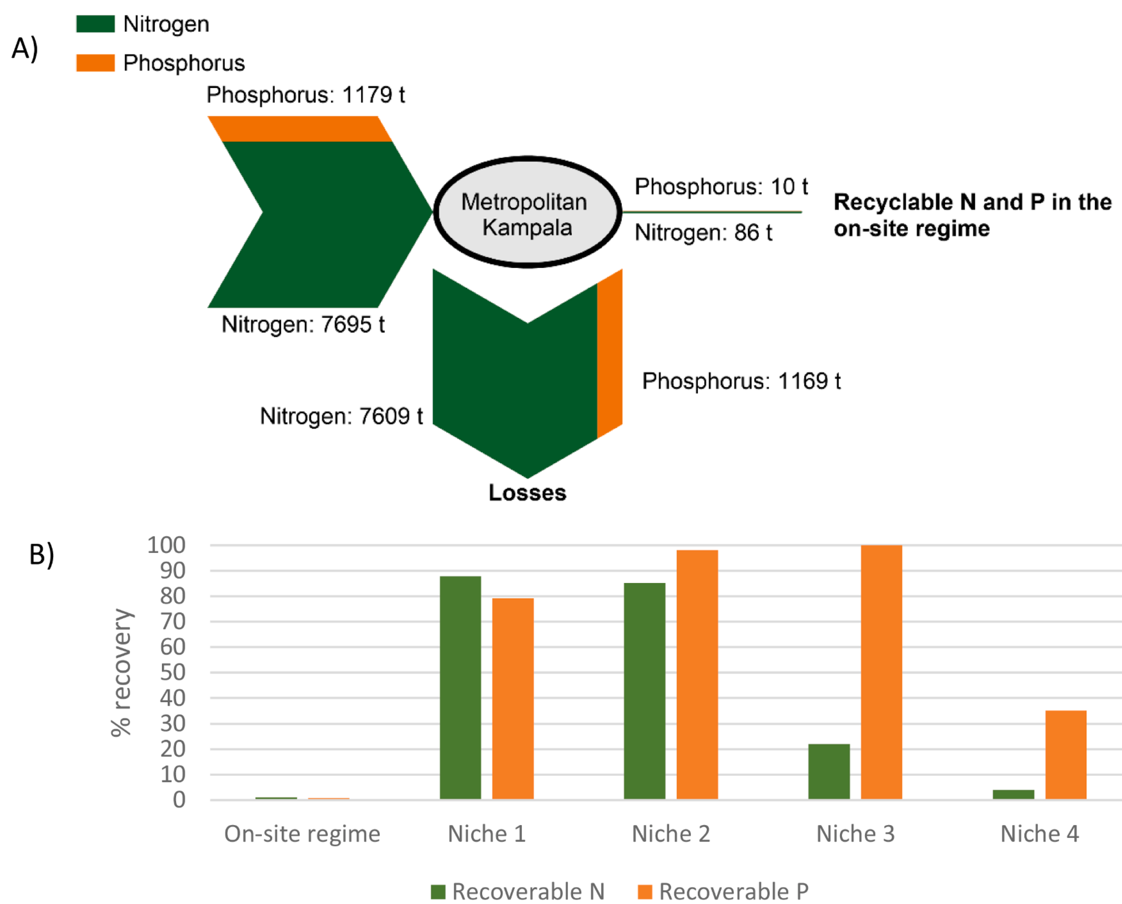

Fig. 2. A) Recoverable nitrogen and phosphorus flows from human excreta in the on-site regime in Kampala, reported in metric tons per year. B) Recoverable nutrient flows in the niches compared to the regime, reported as percentage (%) of nutrients in fresh excreta. Full details of how nutrient recovery was estimated can be found in section B of the supplementary material.

3.4. Sector values

This assessment focused on the norms and values guiding actors' priorities, choices in decision-making and actions within the water and sanitation sector in Uganda. Sector values were identified through a qualitative content analysis of the executive summaries in the Sector Performance Reports (SPR) from the Minister of Water and Environment from 2005 to 2019. Contents of the SPR related to sanitation were coded for content. The coding scheme was informed by common dimensions of decision-making criteria (e.g. economic, environmental, health, institutional, socio-cultural, etc.). Coding was performed in NViVo 11 and results validated during stakeholder interviews. Assessment of niche innovations gauged compatibility or contradictions between sector values and niche goals.

3.5. Policy

The presence of relevant policies, acts and regulation, standards and plans for the on-site regime were analysed through the sanitation service chain: (i) planning/construction/containment, (ii) emptying and transport, (iii) treatment and (iv) reuse. Relevant documents were retrieved and consulted. The preliminary results were validated with stakeholders in 2018, through workshops and semi-structured interviews. It is worth noting that the on-site regime is itself "battling" for policy and legislation space with the sewage regime, which is generally favoured in policies, plans and acts. When relevant, reference will be made to this overarching dichotomy, since preference to centralized solutions will negatively affect not only the on-site regime, but also the niches, which are all on-site.

3.6. Financing

Financing in the regime is characterised by the distribution of costs and revenues between stakeholders, including both capital and operational costs of services. Cost data was collected from local authorities, scientific publications, interviews and field observations. Annualized capital and operating costs were calculated per capita served by the regime (for full cost calculations see McConville et al., 2019). Assessment of the regime focused on whether revenues are to cover costs and if there are any inconsistencies in the division of costs between stakeholders.

4. Results

Overall results of the regime and niche assessments are shown in Table 2. Full results from analysis of each regime characteristic can be found within the supplementary.

4.1. Cognitive - Technology

Assessment of the technology used in the on-site sanitation regime gauged performance levels for safe management and nutrient recovery (details in section B of the supplementary material). The on-site sanitation regime in Greater Kampala is estimated to safely manage 55% of human excreta (McConville et al., 2019). The Kampala Sanitation Master Plan estimates that only 35% of the generated faecal sludge gets collected, thus a fraction of the excreta that is considered safely managed is stored on-site in latrines that are not emptied. A larger proportion of the unemptied faecal sludge is not properly contained,

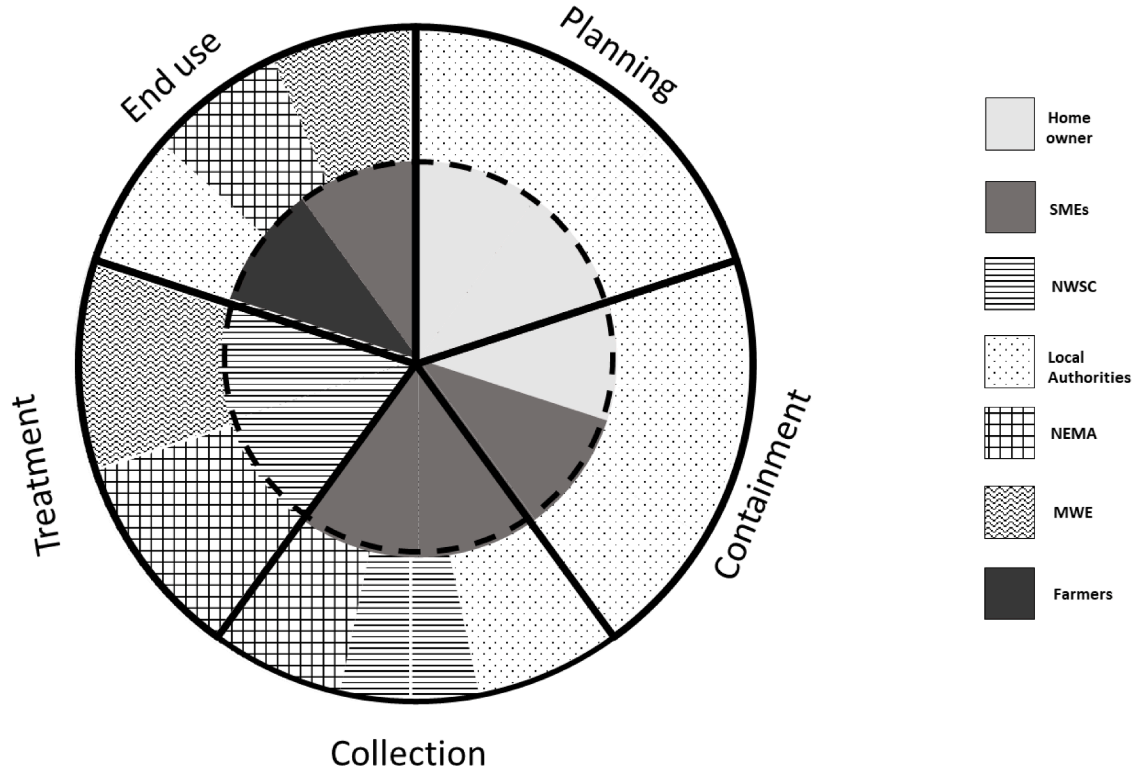

Fig. 3. Overview of organisations involved in the on-site sanitation regime along the sanitation service chain. The inner circle shows actors involved in implementing the service and the outer circle those actors who have coordinating/monitoring roles. Solid colours represent private actors and patterns represent public actors.

leaching from unlined pit latrines into groundwater or leaking into drainage channels and ditches in the urban environment (Niwagaba, n.d.). A previous study, reported that 70% of pit latrines in Kampala's slum were full or overflowing (Nakagiri et al., 2015). Given the rapid urbanization and densification of Kampala, neither safe nor unsafe on-site storage will be sustainable in the long term. Thus, emptying services, and corresponding increases in treatment capacity, are a major weakness in the existing on-site sanitation regime. In addition, the low ability of the sewage regime to expand services to the citizens of Metropolitan Kampala (average of 323 connections per year between 2013 and 2019 (NWSC 2019)), is a general weakness in the sanitation sector that should benefit both the on-site regime and the niches.

Regarding nutrient flows, the existing regime results in nearly a 99% loss of both nitrogen (N) and phosphorus (P) to the environment (Fig. 2). Even if all faecal sludge was collected it would result in a marginal improvement due to the high losses of N and P in faecal sludge management.

All niches perform better than the on-site sanitation regime concerning safe management and nutrient recovery. The complete on-site treatment offered by Niche 3 offers an obvious advantage over the existing regime since all excreta is safely managed on-site. The urine-diversion dry toilets in Niche 1 and 2 are more easily emptied than the traditional pit latrines that currently dominate the regime. In particular, the urine-drying toilet (Niche 2) with the reduced volume of urine would have advantages over the current regime as far as safe emptying and transport. Niche 4 also performs well since the franchise model for toilets increases hygienic conditions at the toilet and regular transportation services to a treatment site will significantly increase safe management. All niches are estimated to considerably increase the recoverability of nutrients (Fig. 2). Niche 2 and 3 are estimated to have recovery rates over 90% for P and Niche 1 and 2 over 80% of N. Niche 3 loses N in the evaporation of urine and Niche 4 does not collect urine at all.

4.2. Cognitive - Epistemic practice

Assessment of epistemic practice in the regime focused on the relationship between knowledge taught at the university and reality on the ground, as well as the level of knowledge taught regarding resource recovery (details in section C of the supplementary material). Curriculum from eight programs for Bachelor of Science and four programs for Master of Science were reviewed from five universities (Busitema University, Kabale University, Kyambogo University, Makerere University, Ndejje University). Courses that cover sanitation represent between 4 and 12% of total curriculum in BSc programs and nearly 30% of total curriculum in MSc programs for water and sanitation or environmental engineering. In half of the twelve programs reviewed, curriculum related to sanitation contained more information related to the sewage regime than on-site sanitation. Three programs contained equal information regarding the two regimes, but no program contains more information related to the on-site regime than the sewage regime. Considering that 99% of the population in Greater Kampala are connected to on-site sanitation systems (McConville et al., 2019), there seems to be a contradiction between epistemic practices at the universities and the existing situation.

The concept of resource recovery is included in all programs except for one at the Bachelor level. Information related to resource recovery is covered in less than 10% of the total courses within each program, with the exception of a MSc program in Environmental Engineering, which includes resource recovery in 25% of the courses. Information related to which resources can be recovered varies between programs. Only two programs include recovery of energy, water and nutrients. Recovery of water is least common in the curricula (5 programs), followed by energy recovery (6 programs) and most commonly nutrient recovery, often in relationship to ecological on-site sanitation (9 programs).

The lack of prioritization of knowledge related to the on-site regime is a barrier for all niches that apply on-site sanitation technologies. This means that sanitation planning is more likely to focus on sewer-based

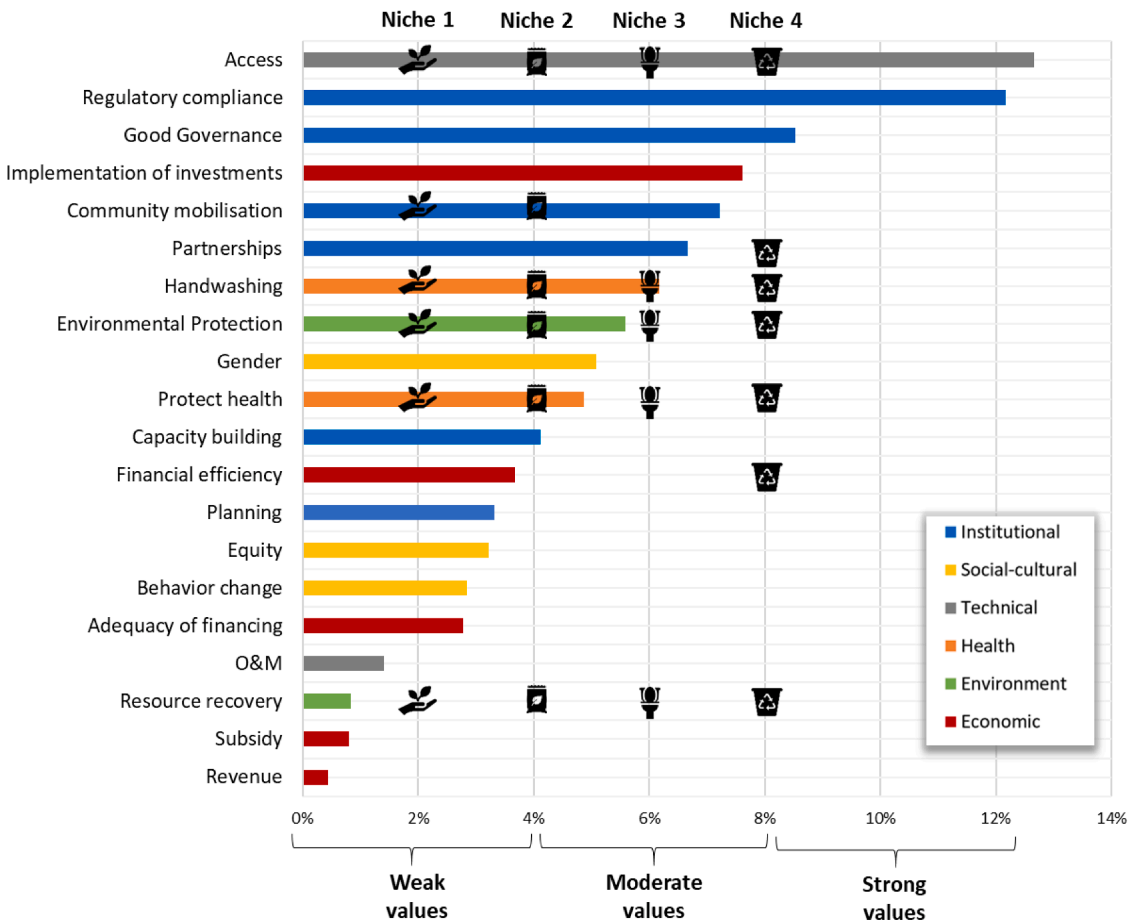

Fig. 4. Sanitation sector values identified in Sector Performance Reports (SPR). The figure shows the average coding density for each value from 2005 to 2019, reported as percentage of all coded text. The colour coding links each value to decision-making dimensions. Guiding principles for each niches are mapped on the values – note they mostly correspond to moderately or weakly cited values.

solutions, rather than on-site options. However, for planning that does focus on on-site options, upscaling systems with UDDT toilets may have fewer difficulties since the UDDT is commonly included in existing curriculum. Thus, based on knowledge available Niche 1 appears to have similar opportunities as the existing on-site regime. The relatively low level of knowledge in the regime concerning resource recovery puts Niche 2, Niche3, and Niche 4 at a disadvantage since they are promoting new forms of resource recovery.

4.3. Normative - Organisational mode

Results of the organisational mode analysis found a diversity and lack of coordination between private and public actors involved (Fig. 3, details in section D of the supplementary material). Implementing actors are primarily private actors: households, small and medium enterprises (SMEs), and farmers, with the exception of the treatment step. Local and national level public actors do monitoring. However, in several cases, several different public actors perform the monitoring. The diversity of actors involved, particularly when performing similar roles, was noted in interviews to lead to confusion in the sector. The end-use stage in particular has a diversity of actors, both in implementing and monitoring, that makes it organisationally challenging.

The diversity of organisational structures may make it easier for new actors and operational modes to enter the regime. However, the diverse regime-scape means that an emerging niche will need to interact and coordinate with a larger number of actors, which can be challenging. Particularly for niches producing new flowstreams (i.e. urine), that requires additional management steps, the initial phase of upscaling the organisational mode will be difficult. Hence, for Niche 1 and Niche 2, transportation and treatment of urine creates an increased demand of organisational capacity. For Niche 3 the high-tech servicing on household level is a role that currently does not exist. It is worth noting that many of the private actors currently involved in implementing the service chain, particularly households and farmers, are weak actors with minimal capacity for organisation. Niches like Niche 4 in which one organisation has the capacity to cover multiple parts of the service chain, including support at the household level, may offer a competitive advantage over the existing system, by reducing the need for cross-organisational coordination. Likewise, the Niche 3 off-grid system combines containment, collection and treatment in one-step, thus simplifying the service chain and corresponding organisation. Depending on how the eco-stations in Niches 1–2 are organised, one actor could manage treatment and end-use, in which case it would offer an advantage to the existing regime. However, in this analysis we have assumed that the organisational structure is similar as that of the on-site regime.

4.4. Normative - Sector values

Contents related to sanitation in the SPRs was coded according to common dimensions of decision-making criteria. As the documents were of different length and density of content, analysis of the results looked at the density of each coded category as a percent of all coded nodes within each document (Fig. 4, details in section E of the supplementary material). The guiding principles of the four niches are mapped against these sanitation sector values.

The most common sector value found in the Sector Performance

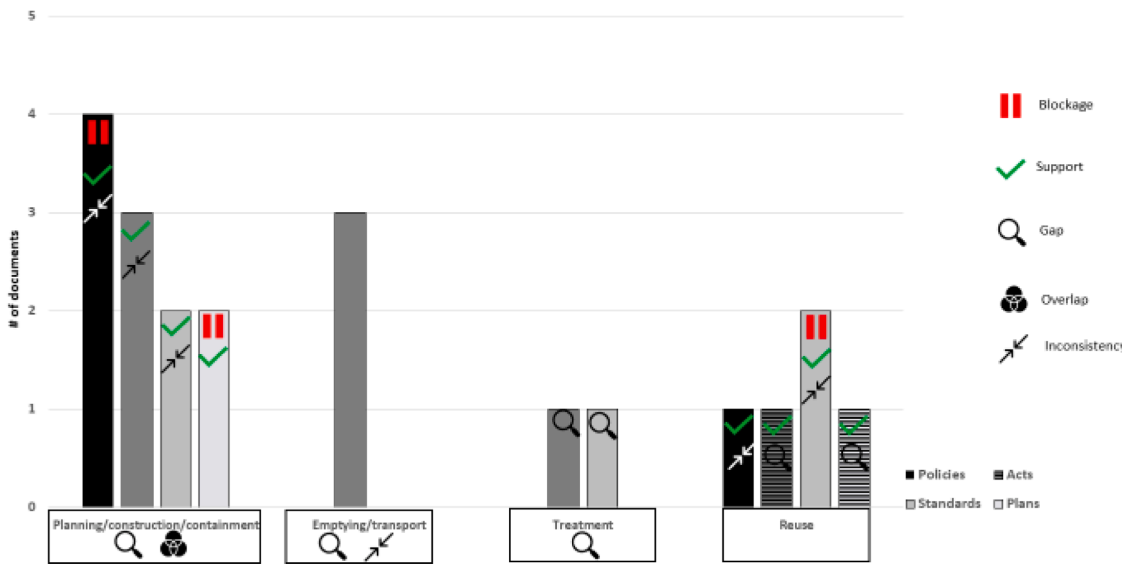

Fig. 5. Number of documents in the categories Policies, Acts, Standards and Plans found along the sanitation service chain with relevant content for the on-site regime. Blockages, support, gaps, etc. are marked for each category along the chain where relevant. Where gaps, overlaps and inconsistencies are related to the planning step as a whole, it is marked under each service chain step. For reuse, there are two columns (Acts and Plans) that are partly filled, i.e. the documents are in place but not directly related to reuse within the on-site regime.

Reports (SPR) was achieving access to sanitation services. Considering that the economic value “implementation of investments” is also related to provision of services, there is a strong dominance of values related to implementing physical infrastructure in the sector. Aside from access, institutional values were most cited, including regulatory compliance, good governance, community mobilisation and partnerships. Less common were values for health and environmental protection and gender and equity. However, regulatory compliance is strongly linked to health and environmental protection, since most regulations are in place for these reasons. Protection of health and environment may thus be implicit values that underlie other values. Less common were references to resource recovery, subsidies and revenue in the sanitation sector.

The strong sector values on access and regulatory compliance support the existing regime and niches equally. Resource recovery and environmental protection are valued in the sector and all niches would be supported by these values. However, these values are not strong values in the sector and it may be difficult to gain traction for the niches based solely on environmental values. This may especially be the case for Niche 3 with its high capital costs, which contradicts moderately strong values for investments.

4.5. *Regulative - Policy*

The policy analysis shows a decrease in overall coverage of policy documents along the service chain (Fig. 5, details in section F of the supplementary material). There are large gaps in policy and only the first step in the service chain is fully covered with relevant documents. Specifically, there is a lack of guidance for the regime in faecal sludge treatment, in spite of the new KCCA ordinance. A large “threat” to the on-site regime is the focus on the sewage regime in policies and plans. This is also a threat to the investigated niches.

There is some general support for the niches expressed, e.g. as recognition of different latrine types in newer regulation and standards (support for Niche 1 and 2 e.g. in The National Sanitation Policy and the KCCA Sewerage and Faecal Sludge Ordinance). Reuse is also included, e.g. the concept of circular economy, cyclical use and processes (The National Environment Act) and an expressed need for local production of fertilizers (The Uganda Fertilizer Policy). There is also a high acceptance for on-site systems for those with space in Kampala (Government of Uganda/NWSC 2015). Gaps that might provide important openings to the niches are too few public toilets in Kampala city and the inadequacy of existing services within the on-site regime.

There are inconsistencies in terms of allowed technology types, which accounts for two of the three inconsistencies in the first step of the sanitation chain. Newer documents seem to consider more options, e.g. the KCCA minimum standards (2017) includes urine diversion toilets. However, the overall construction of guiding documents seems to be around listing approved technologies rather than stipulating functions to be achieved by the technologies. A technology-focused policy and regulation environment is generally inhibiting to innovation (Kvarnström et al., 2011), since innovation may bring new technical systems which are not listed in existing policies and regulation.

Neither the niche systems, nor its products, appear explicitly in the policy texts, because they are new and the policy environment is technology-prescriptive. The dominance in the policy environment by the sewage appears to inhibit the on-site regime and the niches equally. Several blockages against the niches, such as the technology prescriptiveness in building regulation, as well as, the prohibition to use human waste in organic farming, also affect the on-site regime negatively. The factors supporting the niches, such as policy on circular approaches or a general support for locally produced fertilizers, are too general to make a difference for the niches at this point.

4.6. *Regulative - Financing*

Combined annual capital and operating costs for the on-site sanitation regime in Greater Kampala are 14 USD/capita, (details in section G of the supplementary material). Of this, households pay 13 USD/capita/year, of which the majority is capital costs (12 USD/capita). SMEs responsible for collection of the faecal sludge are the only actors in the regime who make a profit as they annually earn 0.11 USD/capita served after capital and operating costs. The water utility has annualized capital and operating costs for treatment of the collected faecal sludge of 0.72 USD, a majority of which is capital costs. Operational costs for treating the faecal sludge (0.19 USD/capita) are not covered by revenues from discharge fees paid by the SMEs (0.11 USD/capita) and sales of treated sludge (0.01 USD/capita), leaving a net operating budget deficit. A key weakness in financing the on-site regime is the lack of cost-recovery from the utility perspective. However, it is worth noting that the sewage system is also subsidized, but to a higher degree (McConville et al., 2019). Total annual capital and operating costs for the utility are over 220 times higher for the sewage system (160 USD/capita) than for the on-site system.

The obvious advantage that resource-recovery niches have is the possibility for increased revenue from sales of recovered products (economic value calculations in Table B.1 in the supplementary material). According to the annual prices data sheets in the World Bank's Commodity Markets, the ten-year average cost of diammonium phosphate (DAP) fertilizer and urea were 399 USD/ton and 294 USD/ton, respectively. This means that the niches could potentially capture nutrients valued at 0.08 USD/capita for Niche 4 (lowest recovered value) to 0.65 USD/capita for Niche 1 (highest recovered value). This could offset the operating deficit in the current regime, but not cover the increased capital costs of the innovations. Thus, it is a weak advantage that is likely not sufficient on its own to drive up-take of the niche. A challenge for Niches 1–3, is that they require increased infrastructure investment that are primarily at the household level and thus capital costs for households increase. This is particularly the case for Niche 3 where all treatment occurs on-site. The exception is Niche 4 since the household level infrastructure is operated on a franchise model that allows the operator to offset the household fee with revenues from e.g. sales of recovered products. The financial model of Niche 4 allows it to overcome one of the key challenges with source-separating systems for resource-recovery, namely the uneven distribution of costs and benefits. Source-separation often results in increased capital costs at the household level, while the benefits of recovered products often remain with the utility or end-users. Another way to increase possibilities for the niches in the on-site regime would be to increase the level of subsidies, either by shifting some of the current subsidies provided to the sewage regime to the on-site regime, or by providing environmental subsidies for nutrient recovery or pollution prevention.

5. Discussion and conclusions

Based on the results of this in-depth study of the existing on-site sanitation regime study, we return to our framework of cognitive, normative and regulative regime dimensions to discuss opportunities for nutrient-recovery innovations to take place. Based on this assessment we can make recommendations for action within each dimension that could enable a transition to more nutrient-recovery in the on-site sanitation sector.

Within the *cognitive dimension (Technology & Epistemic practice)*, the main stress points in the Kampala on-site sanitation regime are inadequacy of safe management and nutrient recovery and an insufficient knowledge level regarding on-site sanitation. Indeed, the dominance of conventional flush sanitation systems as icons for improved sanitation have penetrated most countries in the world, causing lock-in effects and technology choice restricted by lack of imagination (van Vliet et al. 2011). The studied niche technologies offer improved safe management and nutrient recovery compared to today's practice. However, current epistemic practice focuses on sewered sanitation, which is not helpful for the niches. If the epistemic practice were to change and include more on-site sanitation related knowledge this would open up more opportunities for the niches. Indeed, there is increasing focus on non-sewered sanitation within the international sanitation sector (Hoffmann et al., 2020). From a historical perspective, a study of the transition from cesspools to sewer systems in Europe found that cognitive changes that recognized problems with the existing system and the demonstrated improvements by new solutions came first followed by the other dimensions (Geels 2006). It is reasonable to believe that a similar change in cognitive structures is needed to transition the regime from its current state. Perhaps such a shift has started, but current epistemic practice is lagging behind and efforts can be made to actively influence it.

In the *normative dimension (Organisational mode & Sector Values),* the main stress points in the regime are related to unclear roles and responsibilities between actors and weak coordination between multiple actors, particularly in end-use. Indeed, contradictions between different stakeholder values and complex governance structures is a common challenge in the sanitation sector (Ekane et al., 2014). The studied niches are collecting and/or producing more products than in the regime, and hence have increased demands on organisational capacity in the service chain, as well as the need to develop skills and capacities for new ways of doing things. Hence, from the standpoint of organisational capacity, the niches do not currently have a competitive advantage. However, there seems to be opportunities for niches that design their approach in ways that will simplify coordination within the service chain. For example, Niche 3 and Niche 4 offer solutions that can reduce the number of actors in the service chain and thus may have an organisational advantage with regard to coordination. Other case studies have also shown that innovative on-site sanitation solutions can offer advantages with new business models and organisational structures (Rao et al., 2016). Developers of innovation sanitation niches should look for ways to simplify organisational structures when they develop their approaches.

From the standpoint of sector values, we cannot pinpoint stressors within the regime. Sector values in Uganda are dominated by providing access to sanitation, as well as institutional aspects of regulation and governance. Health and environmental protection and gender equality are also valued highly. In many ways, these values reflect the SDGs with goals for sanitation access (SDG 6.2), safe treatment (SDG 6.3) and strong institutions (SDG 16). The guiding principles of the niches are in line with several sector values, including the strongest value of providing access. However, it is difficult to see that any of the sector values will provide specific advantages for the niches. If resource-recovery were more strongly valued in the sector, these niches would have a competitive advantage.

In the *regulative dimension (Policy & Financing),* the regime is under stress from inadequate revenues to cover costs and insufficient policy guiding actions for on-site sanitation. Shortcomings in sanitation policy environments have also been documented in other low and middle-income countries (Helgegren et al., 2021; Weststrate et al., 2019). Similar to this study, these authors also found a dominance of the sewage regime in policy environments. In many countries, including Uganda, the on-site regime is battling for policy space. Similar to the cognitive lock-in related to choice of technology, there seems to be a "policy lock-in" regarding which technologies are approved for use. Reframing existing sanitation policy guidelines from technology-prescriptive to performance-based (e.g. Best Available Technology) may open up for more innovation (Kvarnström et al., 2011).

In addition, the first steps in the sanitation service chain have higher coverage of relevant documents than the subsequent steps including reuse. In particular, there is a lack of policy guidance regarding resource recovery at the end of the service chain for niche products (urine, compost, BSF larvae, dried urine). It could be interpreted that as long as it is not forbidden, that reuse is allowed, which would open up for resource recovery. At the same time, the lack of policy guidance may make certain stakeholders hesitant to enter the market. For example, lack of specific regulations for resource valorisation from wastewater in Europe has been highlighted as barrier to close-loop systems (Cipolletta et al., 2021). Even if the current policy does not significantly hinder the niches, a clearer policy environment for reuse would be desirably.

A significant stress in the current regime is the inadequacy of revenues to cover costs. While all of the niches recover resources and thus have the potential to increase revenues from sales of the reuse products, they also cost more to implement. Thus, it is unlikely that the balance of costs and revenues will change. This is particularly the case with Niche 3 that is significantly more expensive. Niche 4 is the only one that appears to have a competitive advantage concerning financing. This is in part because they do not collect the urine, and thus costs in the service are estimated to be similar to the existing system. The business model used in Niche 4 has seemingly been successfully applied so that costs are covered and shared between stakeholders in a way that makes it affordable to household users. While the scalability of this model in other contexts, including urine management, still needs to be investigated (Russel et al., 2015; Auerbach 2016), this niche has competitive advantages today regarding financial aspects.

While the regime analysis presented in this paper has not been done before in the sanitation context, the situation that it describes is not unique. There are many cities in the world with similar patterns of cognitive, normative and regulatory sanitation practices. Thus, some of the learnings from this study can be generalised to other contexts. First, it is important to recognize that the sanitation sector is still highly influenced by the sewage regime, which is dictating epistemic practice, organisation models and policy. Second, creating space for innovations to thrive will require changes in multiple dimensions of the regime. Third, it will require action on behalf of multiple actors to increase knowledge exchange, try new organisation models and push for policy change. Stakeholder specific suggestions for action based on results of this study include:

- Utilities should pilot innovative solutions in order to demonstrate their advantages and build knowledge.
- Universities should adapt curricula to break the dominance of sewage systems, including more on-site solutions and Best Available Technology (BAT) approach to selection of systems.
- Researchers should disseminate knowledge regarding technical advantages of the niches.

  Niches should focus on possibilities for simplifying organisational structures, streamlining and clarifying roles and responsibilities.
- Policy makers should adapt policy environments to reflect actual and planned reality of sanitation services, including making public funding available for the on-site regime and its niches.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106275.

Appendix

See Table A.1.

Table 3
Definitions and primary data sources for studied characteristics of the socio-technical regimes for on-site sanitation in Kampala.

Characteristic		Definition	Primary data source	Assessment variable
Cognitive	Technology	The physical structures that enable the functioning of sanitation services, e.g. toilets, transportation, treatment plants. Performance assessment focuses on the degree to which they allow for safe recycling of nutrients from human excreta.	Kampala Sanitation Master Plan (Government of Uganda/NWSC 2015) and SFD for Kampala (Niwagaba, n.d.). Literature data on nutrient capture/losses in different technologies. (supplementary material B)	• Adequacy of safely managing waste• Adequacy of nutrient capture/recovery
	Epistemic practice	Availability and content of knowledge related to sanitation services and nutrient recovery.	Course curriculum from five Ugandan universities for BSc and MSc degrees related to environment, civil and water engineering and agriculture. (supplementary material C)	• Adequacy of knowledge regarding systems
Normative	Organisational mode	The group of actors with their corresponding roles and responsibilities for provision of safe sanitation services.	Review of documentation regarding roles & responsibilities for sanitation, triangulated with semi-structured interviews & field observations. (supplementary material D)	• Demand on roles and organisational capacity in the service chain• Coordination between actors
	Sector values	Norms and values guiding actors' priorities and choices in decision-making.	Review of Water and Environment Sector Performance Reports from Minister of Water and Environment (2005–2019). (supplementary material E)	• Compatibility between sector values and niche guiding principles
Regulative	Policy	Specific rules and regulations that govern the service regimes.	Review of existing documents governing sanitation in Kampala: policies, acts, standards & plans, triangulated with interviews. (supplementary material F)	• Inconsistencies or contradictions in the policy environment
	Financing	Distribution of costs & revenues between stakeholders, including both capital and operational costs of services.	Budgets from local authorities, scientific publications, interviews & field observations (McConville et al., 2019). (supplementary material G)	• Adequacy of revenues to cover costs• Inconsistencies of division of costs between stakeholders

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