Socio-technical analysis of a sanitation innovation in a peri-urban household in Durban, South Africa

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HIGHLIGHTS
• Assessing a novel toilet requires input from engineers, social scientists and users.
• Existing sanitation and the exceptionalism of testing affect social acceptance.
• Users have a high tolerance of sanitation failures, but this system functioned well.
• Users wanted more detail on the science of water recycling from trusted informants.
• Transdisciplinarity is central to the development of socially just sanitation.

GRAPHICAL ABSTRACT

ABSTRACT
The provision of water and sanitation for all that is safe, dignified, reliable, affordable and sustainable is a major global challenge. While centralized sewer-based sanitation systems remain the dominant approach to providing sanitation, the benefits of non-sewered onsite sanitation systems are increasingly being recognized. This paper presents the outcomes of the testing of the Blue Diversion Autarky Toilet (BDAT), a sanitation system providing hygiene and dignity without relying on water and wastewater infrastructure, in a peri-urban household in Durban, South Africa. The BDAT was used by a single household as their only form of sanitation during three months of technical and social testing. An analysis based on technical data in combination with interpretive, qualitative research methods revealed that the BDAT functioned well and achieved high levels of social acceptance in the test household. The flushing, cleanliness and odour-free nature of the sanitation technology, its functionality, the household’s previous sanitation experience, and their experience with and understanding of water scarcity, were the main factors underpinning their positive response to this innovation in sanitation. The testing process resulted in broader developmental benefits for the household, including improved basic services due to the upgrading of the electrical and existing sanitation system, social learning, and improved relationships between household members and the local state. A transdisciplinary research process, which emerged through the assessment, enabled the integration of different forms of knowledge from multiple actors to address the complexity of
problems related to the development of socially just sanitation. The benefit of engaging with societal actors in sanitation innovation and assessing its outcomes using both the technical and social sciences is evident in this paper.

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1. Introduction

The provision of hygienic, dignified, accessible and environmentally-sustainable sanitation is essential to human health and well-being. However, universal provision of sanitation remains a challenge, particularly in countries in the Global South. Here, rapid urbanisation, with its resultant informality and sanitation backlogs; poverty and inequality; water security challenges; failing infrastructure; and lack of institutional capacity undermine efforts to ensure safe sanitation for all. As a result, achieving Sustainable Development Goal 6 on clean water and sanitation remains a challenge, with 2.3 billion people still lacking basic sanitation services in 2018 (United Nations, 2018). Centralized sanitation systems, which depend on access to significant quantities of water, the provision of sewer-based infrastructure at scale, and wastewater treatment plants, remain the dominant approach to providing sanitation services (Bhagwan et al., 2019; Satterthwaite et al., 2019; Larsen et al., 2016). However, the sustainability and feasibility of a centralized infrastructure approach in the face of large global sanitation backlogs and environmental change is under debate. Consequently, innovation in sanitation is focusing on affordable, safe, non-sewered on-site sanitation systems, which support resource recovery (Bhagwan et al., 2019; O’Keeffe et al., 2015). On-site treatment and source separation, especially in combination, open up the potential for locally-adapted water and sanitation services and the recovery and reuse of valuable resources (Larsen et al., 2016).

The Bill & Melinda Gates Foundation’s Reinvent the Toilet Challenge (RTTC) has inspired a wave of research on next-generation on-site sanitation technologies designed to operate off-grid (i.e., without external water supply and sewers), recover resources from toilet waste, and, ideally, cost less than USD 0.05 per person per day. Prototypes of these technologies are being field-tested in peri-urban areas, informal settlements and research institutions in South Africa and India. This paper presents the approach adopted in and the outcomes of the testing of the Blue Diversion Autarky Toilet (BDAT) in a household in a peri-urban area in Durban (eThekwini Municipal Area), South Africa.

The adoption of new sanitation technologies does not depend on technical functionality alone. Lack of social acceptance is a frequent cause for so-called “failed technologies” (van Vliet et al., 2011). However, the socio-cultural meaning and use of toilets receives less attention than the technical design and functionality of innovative sanitation systems. Various publication on field tests of novel sanitation systems have been published over the past few years (e.g., Sahondo et al., 2020; Varigala et al., 2020; Welling et al., 2020; Henngis et al., 2019; Cid et al., 2018). While these publications evaluate and compare the technical functioning of such sanitation systems, they provide no or only limited information on their social acceptance.

Social acceptance of sanitation systems, by individuals, families and broader societal groups, is shaped by socio-economic, political, cultural, historical and geographical factors. These factors need to be taken into account in the co-production of knowledge for technology design to ensure the delivery of sustainable and affordable sanitation systems that meet the needs of people (Sutherland et al., 2016; O’Keeffe et al., 2015; Sutherland et al., 2015; Jenkins and Scott, 2007). Engineering field testing therefore includes both the technical testing of technologies, as well as understanding and analysing the social responses to it, to ensure that next-generation sanitation technologies are scientifically, politically and socially acceptable. This is aligned with a transdisciplinary (Td) research approach, which supports socially relevant research that addresses societal problems, taking into account multiple forms of knowledge (Pohl et al., 2017; Vogel et al., 2016; Bhaskar et al., 2010). In Td research, researchers from different disciplines work together with societal actors in a collaborative learning experience to co-produce knowledge and solve complex socio-ecological problems (Pohl et al., 2017; Bhaskar et al., 2010; Max-Neef, 2005). While the scientists testing the BDAT in a real-world context in Durban did not explicitly adopt a Td research approach at the outset of the testing, the research methods used by both the engineers and social scientists resulted in an emergent Td research process, which proved valuable in the assessment of the technology, as this paper will show.

Integrating both, technical and social knowledge in the development and testing of innovative sanitation technologies may contribute to socio-technical transitions, or at least socio-technical niches (Fuenfschilling and Truffer, 2014). The “socio” in “socio-technical” is, however, often under-recognised in literature, especially in a developing country context (Steelman et al., 2015). Geels (2010) and Markard et al. (2012) view socio-technical transitions as a fundamental change in systems which involve not merely new innovative technologies, but also changes in user and institutional practices, and in cultural and policy meaning. A wide range of social, technical, political, institutional and economic factors enable and constrain socio-technical transitions (Geels, 2010; Smith et al., 2010). Three factors which are relevant to this study include changes in technology design and functionality; changing perceptions; and social learning. These factors were considered in the analysis of the outcomes of the testing of the BDAT in Durban.

Socio-technical transitions can take place at different scales, with socio-technical niches operating at a microscale, drawing on the knowledge of “small networks of actors learning about new and novel technologies and their uses” (Hodson and Marvin, 2010). This is relevant to the results of this study, where a single household was used to test the BDAT system, as a result of the constraints of testing sanitation prototypes in the real world.

The paper therefore presents the socio-technical relations produced through the introduction and testing of an innovative sanitation technology in a household in a peri-urban area that previously had access to urine diversion dehydration toilets (UDDTs). This work contributes to knowledge on practicing Td research and to the nature of socio-technical transitions in sanitation provision that develop at the microscale. Most importantly, the paper presents the socio-technical results of testing an innovative sanitation technology in the field, making recommendations about its future use at scale.

2. Background

2.1. The Blue Diversion Autarky Toilet (BDAT)

The BDAT, a collaboration between the Swiss Federal Institute of Aquatic Science and Technology, Eawag, the design office EOOS, the Paul Scherer Institute (PSI) and the University of Applied Sciences of Northwestern Switzerland (FHNW), was developed as a possible answer to the sanitation crisis in urban slums (www.autarky.ch). In the BDAT, water, urine, and feces are collected separately and treated on-site in specific modules. The BDAT recycles water for toilet flushing, recovers nutrients for fertilizer production and reliably inactivates pathogens (Riechmann et al., in preparation; Reynaert et al., 2020).

A prototype of the BDAT was tested in one household over three months to evaluate its technical functioning and social acceptance,
and to assess if this form of sanitation is an appropriate sanitation solution for peri-urban peripheries in Durban and the developing world.

The development of the BDAT drew on different disciplines, as it resulted from a collaborative effort between designers (frontend and superstructure), and scientists and engineers (backend technologies). User feedback from field tests of the previous Blue Diversion Project in Kampala, Uganda, also impacted the final design (Tobias et al., 2017; O’Keefe et al., 2015), as did understanding of the low acceptance of the UDDTs implemented in the test location. Dominant concerns with UDDTs were the emptying of the dehydration chamber, pedestal malfunctioning, smell, low quality of the toilet structure, and users aspiring to have flush toilets (Mkhize et al., 2017; Roma et al., 2013). The BDAT was thus designed around three guiding principles:

1. Safety and comfort: The BDAT offers the safety and comfort of a modern flush toilet without requiring piped water or sewerage.
2. Source separation: Pathogen inactivation, nutrient recovery, and water recycling for flushing and hand washing are achieved by the separate and automated treatment of feces, urine, and water.
3. Modularization: A modular design allows for a wide range of designs and applications. Single modules can be used alone or combined with other technologies.

2.2. The Engineering Field Testing platform

The technical and social testing of the BDAT took place through the Engineering Field Testing (EFT) platform in Durban, which is a collaboration between the University of KwaZulu-Natal (Pollution Research Group and School of Built Environment & Development Studies), eThekwini Municipality (eThekwini Water and Sanitation Unit, EWS) and Khanyisa Projects, a development and engineering firm. The EFT’s transdisciplinary team leads and facilitates the testing of prototypes of innovative sanitation technologies in the eThekwini Municipal Area. A local team of engineers and social scientists supports technology developers through site selection, community engagement, ethics approval, site preparation, installation and commissioning, sampling, testing (social and technical) and decommissioning of prototypes (Mercer et al., 2018).

2.3. Context of the Blue Diversion Autarky Toilet field testing

The BDAT was tested in a peri-urban area of Durban, which still reflects the inequalities of service provision produced by apartheid. To address service backlogs and provide a basic level of water and sanitation universally across the municipal area, eThekwini Municipality has adopted a spatially differentiated approach to service delivery (Odili and Sutherland, forthcoming; Sutherland et al., 2014). Durban has an urban core and rural periphery, which are demarcated by the Urban Development Line (Sim et al., 2016). In the urban core, residents predominantly have access to waterborne sanitation. In contrast, indigent residents have been provided with UDDTs by eThekwini Municipality and or have self-installed pit latrines and, in some cases, flush toilets connected to septic tanks in the peri-urban and rural periphery, which is not serviced by centralized sewer infrastructure. More information on the history of sanitation provision in the eThekwini Municipal Area is provided in Supplementary Information (SI) section S.1.

The BDAT was installed and tested in a peri-urban household in Mzinithi, which falls under the dual governance of eThekwini Municipality and the Qadi Traditional Authority (Sim et al., 2018). The majority of households in the area use UDDTs, or modifications of them, as their primary sanitation facility. In most cases, sanitation facilities are located outside the household in the yard, some distance from the dwelling. SI sections S.2. and S.3. provide detailed information on the governance system and on the type of UDDTs implemented in the area. While there is a high use of UDDTs in Durban, research has shown that respondents are not satisfied with them, due to their smell, the emptying process and the poor craftsmanship of the superstructure (Sutherland et al., 2019; Mkhize et al., 2017; Sutherland et al., 2016). Until recently, emptying the chambers of the UDDTs was the responsibility of household members, with concerns raised about impacts on dignity, hygiene and exposure to health risks. In response to these concerns, EWS rolled out a programme in 2017–2018, where contractors emptied the chambers on behalf of the municipality (Sutherland et al., 2019). However, UDDTs fill up quickly in larger households and the second phase has not, as yet, been implemented. EWS is currently reviewing its policies and practices with regards to the provision of sanitation to the urban poor. A more diverse and decentralised sanitation system is starting to emerge, with the EFT platform contributing to this process (Odili and Sutherland, forthcoming).

3. Methodology

3.1. Ethics statement

The methodologies used for this study were approved by the Research Ethics Committee at UK2N (approval numbers BE/045/19 and HSS/0153/019).

3.2. Engineering field testing process, household selection and interview design

Technology developers supported by the RTTC are testing prototypes in Durban through the EFT platform. Prototype testing results in sanitation technologies being tested in a single to a few households, or, in the case of communal sanitation facilities, in a particular settlement or school. This is due to only one or a few prototypes being manufactured, as cost and testing requirements are a challenge. As a result, testing and evaluation are undertaken at the microscale, with in-depth interpretive, qualitative assessment adopted for evaluating the social acceptance of the prototype (Flick, 2018; Mottier, 2005). Members of the EFT platform collectively decided on the choice of the case study site, based on a range of criteria for the testing: an accessible household that was willing to participate in the prototype testing, and which reflected typical characteristics of households in peri-urban areas, with access to a functional UDDT in their yard. Once the identified household had been approached jointly by the municipality’s Community Liaison Officer (CLO) and engineers from Khanyisa Projects about their willingness to participate in the testing process and had agreed, the CLO met with the ward councillor to obtain permission to test the BDAT in the area. Permission for testing was also requested and granted from the inkosisi, the leader of the Qadi Traditional Authority. Once permission from the authorities had been obtained, the CLO met with the head of household to explain the research programme and the process of testing the prototype in more detail, and to introduce the household to the social assessment process. The social assessment researchers then met with the household members to discuss their role in producing knowledge with the household, around their experience of testing the toilet.

The BDAT was tested in a single traditional household that comprised of the main house, as well as a cluster of three houses adjacent to the main house for extended family members. Fourteen family members were living in the household during the prototype testing, of which eight were female and six male. The family has lived in this house for over twenty years. Qualitative data was collected in three phases: through a pre-testing questionnaire, a mid-test interview and a post-test interview with two members of the household. The interviews included only female participants, as the males in the household were under 18 years old and hence were excluded for ethical reasons. Two female household members reported on their perceptions, attitudes and feelings about the testing and functioning of the BDAT in their household. They also reflected on the perceptions, attitudes and experiences of the children, which included the male members of the household, as well as other household members. They had been informed at the
outset of the testing that all the voices and experiences of residents of the household were important in assessing the BDAT, and that they would be asked to share this information with the researchers in the interviews. The data presented here is thus framed by female perceptions and knowledge of the system.

The first-phase pre-installation questionnaire focused on the existing sanitation services and practices of the household, their response to being part of the testing of the BDAT and their attitudes towards recycling water. The second-phase mid-test semi-structured interview was conducted to determine how the BDAT had been functioning and the family’s response to the toilet and the testing process. The last phase was an exit semi-structured interview to assess the household’s toilet experience, their satisfaction with the technology, their experiences of the testing process, and the transition from the BDAT back to the UDDT. The post-test interview was conducted one month after the system had been removed from the household. The questionnaire and interview questions are included in Supplementary Information Section S.4. The interviews were conducted in isiZulu, recorded, transcribed and translated to English. Field notes were recorded by the researchers on each visit with the family. To ensure triangulation, the interviews were translated by the researchers both during the interview process and from the transcriptions. The head of household was the main participant sharing her knowledge in all three qualitative engagements with the social science researchers, but other female household members attended these engagements, in which knowledge was shared, with one other female household member providing input.

The responses of the household to the sanitation technology were analysed and interpreted using five analytical themes: (i) the functioning and experience of the sanitation system (ii) the position of the household in the history and geography of sanitation services in Durban, (iii) the household’s responses in relation to their previous sanitation system, (iv) social learning and reframing of local knowledge, and (v) participation in a transdisciplinary research processes.

3.3. Implementation design of the Blue Diversion Autarky Toilet

At the household’s request, the BDAT was installed next to the household’s existing UDDT, so that it could not be seen from the main street (Fig. 1). The BDAT requires a regular and stable electrical supply, which required an upgrade of the household’s electricity system to respect South African electrical compliance requirements.

3.3.1. Test toilet

The BDAT used in this testing consisted of the front end user interface with separation of water, urine, and feces, and two backend technologies for water and urine treatment (Fig. 2). As the feces treatment module developed by the Blue Diversion Autarky project was not ready for field-testing, feces were collected onsite in a sealed container that was removed from site and disposed into a sewer twice per week.

3.3.2. Toilet superstructure

The main characteristics of the toilet superstructure were defined by the engineering requirements: (i) the dimensions were derived from the space requirements of the treatment modules and resulted in a footprint of 4 m², (ii) the toilet cabin had to be elevated (and thus accessible up five steps) to allow for gravity flow from the user interface to the urine treatment module and feces collection tank, and (iii) access to the modules from all sides for maintenance was possible through wing doors. The water treatment was located behind a false wall within the toilet superstructure, while the urine treatment and feces collection were below the toilet cabin.

3.3.3. User interface and source separation

Significant attention was paid to the user functionality and attractiveness in the detailed design (Fig. 3). By providing an electrical light, a handwash basin with a soap dispenser and a mirror, a trash bin for menstrual hygiene products, a ventilated window, and a door which could be locked from the inside, the toilet provided all necessary comfort features of a modern toilet. The handwash water tank could be refilled with tap water, and biodegradable soap (recipe from Ziemba et al., 2018) was provided.

The front end of the BDAT consisted of a urine-diverting water-flush toilet (save!, Keramik Laufen AG, Laufen, Switzerland) and a dry urinal (LEMA, Keramik Laufen AG, Laufen, Switzerland) (Fig. 2, upper left). The flush water passed through a solids separator (Separator, Aquatron, Västerås, Sweden) to separate the used water from the solid fraction (feces and toilet paper). The toilet, urinal and handwash facilities were located in the toilet cabin, which was part of the main toilet.

Fig. 1. Photograph of the Blue Diversion Autarky Toilet (BDAT - right) beside the household’s existing Urine Diversion Dehydration Toilet (UDDT - left). The peri-urban area of Mzinyathi can be seen in the background.
superstructure. The superstructure and outside appearance of the BDAT were designed by the Austrian design office EOOS.

3.3.4. Water treatment

The water treatment system, referred to as Water Wall, treated and recycled the toilet flush water separated from the major part of urine and feces. The system has been described in detail in Reynaert et al. (2020). In short, a multi-barrier approach with four treatment stages ensures that the water is safe for reuse (Fig. 2, right hand side). The first barrier is an aerated bioreactor, in which active biomass is responsible for carbon oxidation, nitrification, and denitrification. As the second treatment barrier, the water is filtered by gravity through an ultrafiltration membrane. The combination of bioreactor and membrane is called a biologically activated membrane bioreactor (BAMBi). The filtered water is pumped into a clean water tank (CWT). In the CWT, a granular activated carbon filter acts as a third barrier, removing remaining organic contaminants by adsorption and biological degradation. Finally, the fourth treatment barrier, an electrolysis unit with water recirculation, further reduces the organic carbon concentrations and produces a chlorine residual, both of which help to limit pathogen growth during storage.

The water treatment included a range of electric components: an air pump for aeration, three submersible pumps (pumping the wastewater into the bioreactor, pumping the filtered permeate into the CWT,
recirculating the water through the electrolysis unit), and an electrolysis unit, resulting in an overall energy requirement of 1.2 kWh/day for the water treatment unit.

3.3.5. Urine treatment

The urine treatment module produces a solid fertilizer from source-separated urine. The system has been described in detail in Riechmann et al. (in preparation). The system relies on two processes to treat the urine in the toilet: urine stabilization and water removal (Fig. 2, bottom left). During the stabilization, the pH of the urine is increased to values above 12 through the addition of calcium hydroxide (hydrated lime). This elevated pH value prevents microbial urea hydrolysis, thus preserving the nitrogen in the solution and preventing malodor originating from fermentation and ammonia release, and deactivates pathogens. Water removal is achieved in an evaporation unit, in which a system of stacked flat basins creates a high surface area. Fans generating a high air stream accelerate the evaporation of the water from the incoming urine. The off-gas is filtered through an activated carbon filter, preventing the emission of organic contamination or malodor. The system relies on a monthly service, during which the calcium hydroxide depot is refilled and the dried urine concentrate is harvested. The end-product is a concentrate of inorganic and organic nutrients that could be used as a fertilizer in agriculture.

The urine treatment included two types of electric components: nine fans to enhance the evaporation of the water and a mixer to bring the fresh urine in contact with the calcium hydroxide, resulting in an overall energy requirement of 1.2 kWh/day for the urine treatment unit.

3.3.6. Maintenance

An operator was on site two to three times per week to take water and urine samples for laboratory analyses, discharge the feces off-site into a sewer, and check that all system parts worked properly. As part of the regular maintenance, the operator also refilled water into the systems to compensate for the losses due to evaporation and losses at the solids/urine separation, and supplemented sodium chloride to the water to balance chloride losses from chlorine volatilization. Once per month, the concentrated urine product was harvested and calcium hydroxide was refilled to the urine stabilization reactor.

4. Results

The BDAT was tested in a single household as part of the EFT platform from March to June 2019. The results of the field testing of the BDAT system comprise both the technical and social assessment of the system. The response of the household to their participation in an emergent Td research process, which included the presence of, and their engagement with, engineers, social scientists and a new toilet technology in their household, is first presented. The household’s response to the BDAT and their experience of using it, which is shaped by both the design and functioning of the BDAT and their previous sanitation experiences, reveals how well the BDAT worked in reality. The final section reflects on the potential of socio-technical transitions at the household-scale, as it presents the household’s response to using recycled water within a sanitation system.

4.1. Transdisciplinarity in the testing of the Blue Diversion Autarky Toilet

The household formed a central part of the EFT platform for the testing of the BDAT. The family members participated in the co-production of knowledge for the evaluation and future development of the BDAT, both through their use of the system and their response to it. The household began to influence the testing process once they had been selected for and had agreed to participate in the EFT process. For example, the household members contributed to decisions about where the BDAT would be located. The inclusion of the household in decisions about the testing process, such as how the toilet would be used and assessed, resulted in a stronger sense of ownership of the toilet and reflected some control by the household in the testing process. The inclusion of the household members in the testing process from the outset increased their positive response to the process and created a stronger attachment to the technology, which shaped their protective behaviour towards it. The head of household stated that she felt responsible for the BDAT, as it had been placed in her household, which she felt was an honour and a privilege with her consent and her involvement in the testing process.

As a result of the testing process, a network of actors was established in the Td research space, who regularly interacted with each other to test the prototype (Fig. 4).
The engineers engaged with the household regularly. According to the head of household, the engineers built a good relationship with the household and offered valuable support around the functioning and maintenance of the BDAT system (Respondent 1, 25/07/2019). The system was well-developed and relatively self-sufficient, however, it required ongoing monitoring due to the testing process. The engineers therefore visited the household frequently, resulting in a unique situation, where the municipality (through the EFT process) was directly engaged with its citizens (the peri-urban household) around service delivery. This ensured that the BDAT functioned well and that failures were addressed immediately. However, it must be noted that this kind of exceptionalism as a result of the socio-technical field study would not be the case if the prototype was rolled out as a sanitation system, and hence the robustness of the system outside of the realm of this form of exceptionalism is important.

The head of the household was satisfied with the process undertaken by the municipality to introduce her to the BDAT. She was happy that the toilet would be tested on her property, stating that “I am going to use a flush toilet as the other people use” (Respondent 1, 18/02/2019). The initial response of the household to being selected as a test household was related to the material and state-citizen benefits the household would obtain, namely access to a flush toilet and access to support around service provision from the municipality in their household. This made them feel special in relation to their neighbours (Respondent 1, 03/05/2019). They felt they would be part of contributing to a legacy of improving sanitation provision in Durban, South Africa and internationally, and it also meant that the municipality “knew that they were there and what services they had access to” (Respondent 1, 03/05/2019). Being recognised and acknowledged by the municipality has been raised by other households and community participants in the EFT process as being a positive and important outcome of the technology testing processes.

Being selected as a participant in the EFT platform can have social impacts on a household, including disruptions to their daily life, having to allow engineers to access their homestead regularly and being singled out in their community. This can lead to social conflict and marginalisation, as others question why the household was selected. The household members had been concerned that “even though nobody said anything, the community would say ‘why us’” (Respondent 2, 03/05/2019). Once the neighbours understood that this was a short-term test and that the household was participating in municipal research “they were happy seeing a beautiful thing in our yard. They were even complimenting the toilet, but we told them it was leaving. They wished it would stay forever. Then we would say, maybe it would happen that it comes back” (Respondent 1, 03/05/2019). This reveals the power and knowledge the household testing the technology was given in the neighbourhood, to share insights with their neighbours and community about new sanitation technologies that may be introduced in Durban. However, the household was cautious about using this power, as they were very aware of the discussion on why they had been selected and did not want this to create social and political problems for themselves.

The household members expressed the desire to be included in capacity building processes, where they could learn about the science of the new sanitation system. The head of the household stated that she was not initially given information about how the urine diversion process worked prior to the BDAT being installed (Respondent 1, 03/05/2019). At this point, she wanted to have more information on how the toilet worked, how the urine and feces were treated in the BDAT and what the impact would be if she used soap and chemicals in the toilet. She believed that the municipality and Khanyisa Projects (as the installation partner) should provide her with this level of information. The engineers provided the household with information on the urine and feces treatment process when the system was installed. The head of household appreciated gaining this knowledge and reported that she had been provided with sufficient information on the system (Respondent 1, 03/05/2019).

4.2. Socio-technical responses to the Blue Diversion Autarky Toilet

All household members used the BDAT. The boys used the urinal in the BDAT, but also continued to urinate outside. Neighbours came to see the toilet, but the head of the household did not allow anyone from outside the household to use the toilet, unless they were visitors to the household, as she was concerned they would not use the toilet correctly. The head of the household also explained that they did not allow others to use it because “we were asked about the number of the people that are living in this household and we were told not to let other people use it, because they would not know if someone goes in there and breaks something. Even the children from the neighbours, if they come to play and go to the toilet, we follow them to make sure they do not break anything. That is why we even lock it, so that they can not go there anytime” (Respondent 1, 03/05/2019).

The children were able to use the BDAT after they had been taught by the mothers about how it worked, and they found it very easy to use. According to the head of household, the children used the toilet the most. She stated that when the children “want to go to the toilet they even queue to wait for the other one inside. Even if you tell them to go use this one [UDDT], they say, no we want to use this one [BDAT]” (Respondent 1, 03/05/2019).

The household members were asked if any of their sanitation practices changed while they were using the BDAT. The head of the household stated that they did not dispose off pampers (disposable nappies) and menstrual hygiene products in the toilet, the way they used to do when they used the UDDT. She said that “the young ones and the girls used to throw the pampers and pads in the UDDT, but this does not happen in this toilet. So things have changed. But with this one [the BDAT], they are very careful because they look after it” (Respondent 1, 03/05/2019). They now dispose of nappies and menstrual products in plastic bags and put them in the plastic bin for waste removal. Household members strictly adhered to the rule of not disposing of solid waste in the toilet. Whether this will remain a practice over the long term, if similar toilets are installed more widely, is of concern to EWS based on the unit’s experience of the challenge of solid waste being disposed of in toilets across the city. This is an important issue in the design of sanitation technology, as solid waste can impact on the functioning of the system and the management of its waste products.

Table 1 shows that, from a technical perspective, the BDAT superstructure, user interface, water treatment module and urine treatment module functioned well throughout the testing, however, there were some incidents that necessitated interventions of the operator. While some incidents were apparent to the users and reported directly by them, others were only detected by the operator. Critical incidents were water leakages due to loose connections and a pump turned off by the system operator, both resulting in the unavailability of water for toilet flushing. The household members also noticed leakage of the handwash tap and one event when toilet paper was not correctly flushed out of the toilet bowl. Incidents that were detected only by the system operator were linked to the process functioning (changes in the water quality, nitrogen loss in the urine treatment) and a partial blockage of the Aquatron separator which affected the separation of water and solids. Except for the two incidents described above (leakage, no refill of the CWT), water was available in the CWT throughout the testing.

The technical testing revealed that there were no problems with the design of the superstructure. However, in the household interviews, the head of household, who was responsible for cleaning the toilet, stated that the material used for the floor of the toilet structure was difficult to clean, as it was a rough surface and hence the mop did not move easily over it. She stated that “maybe it was not meant to be mopped. It was difficult when you try to wipe it, but maybe it was not allowed” (Respondent 1, 25/07/2019). She would have preferred a floor surface that she could clean easily, as this was important to her.

According to the household members, the BDAT system functioned very well and did not have any major failures. The head of household
Table 1

Incidents that occurred during the testing of the BDAT, divided into those that were apparent to the users and those that required detection by the toilet operator. An evaluation was made in terms of (●) no incidents; (●) incidents that were not critical to the functioning of the system; (★) incidents that were critical to system functioning.

| Technical assessment | Interview responses |
|----------------------|---------------------|
| Incidents not apparent to users | Incidents apparent to users | |
| Superstructure | ● No incidents | ● No incidents |
| User interface and feces collection | ● Blockage (day 74): Accumulation of toilet paper in the solids separator, which may have affected the degree of solids separation. | ● Leakage (throughout the testing): The handwash water tap leaked. This had no effects on the functioning of the BDAT, but prevented the household from refilling the handwash water tank. |
| Water treatment | ● Process (day 63): An extended power outage (> 12 h) impacted the biological treatment and led to transient increased nitrite concentrations in the water. While nitrite is not per se a problem for reuse as handwashing water, it can be a health concern in case of accidental consumption of large quantities. | ● Leakage (days 0–7): The connection from the CWT to the flush cistern was not tight during the first two days of operation and water leaked to the ground, which was detected and reported by a member of the household. |
| Urine treatment | ● Process: A substantial part of the nitrogen was lost from the urine during the evaporation of the urine-water, lowering the quality of the final fertilizer. | ● No incidents | ● No reports |

reported the water leak from the handwash water tap, the water leak from the toilet after the installation and the problem with the flushing when the pump had been turned off in error. However, these issues were not of major concern to the household, as the engineers fixed most of the problems quickly. The only permanent problem was the leaking handwash tap, which was due to a fault in the design of this unit, which had been purchased from a local sanitary hardware store. The household members reverted to their previous practice of post-toilet handwashing, which was to use the yard tap. This was not considered to be a major inconvenience to the household members. Interestingly, the household members did not report all of the failures to the engineers, most likely because they had a relatively high tolerance for water and sanitation failures, given their experience with their previous water and sanitation systems. The household members reported that there was always water in the toilet, which reflects that the two incidents without water were not deemed to be major problems.

Household members reported that the flush worked well and every time someone flushed, all the waste was taken away and the system filled up quickly again for the next flush. They reported that the toilet flush did not work at one point, but this was not of major concern as “even when we had a flushing issue when the waste was not going, we called the engineer and he came and fixed it” (Respondent 1, 25/07/2019). The household members stressed that in all cases the problem was fixed within a short time frame: “We have reported the fault, yesterday or the day before yesterday. When we were using it, it could not flush. We then called the CLO to report it, he called the engineer and yesterday they came to fix it” (Respondent 1, 03/05/2019). According to the household members, water was always available in the BDAT, as the engineer always came and filled it up if there was no water (technically: water addition to account for water losses to urine and feces treatment and evaporation).

The engineers had been concerned that the slight buzzing sound generated by the urine treatment module fans may be a nuisance to the user, and that if the system failed, there may be an odour from the urine. The household members did not raise either of these possible challenges as an issue, stating that the toilet was very comfortable, they could relax in it, and that there was no smell that emanated from the system.

During the field testing of the prototype, the household members were asked what they thought of the BDAT and their experience of using it. The household members said that they “loved the toilet” and that it was easy to use. Household members stated that the flush was its best feature, that they appreciated the cleanliness of the toilet, its lack of smell, its design and comfort, and the ability of the door to lock. The head of the household remarked that in a UDDT “when the children go in there, they take off their clothes and leave them outside, because they do not want to come out with the smell” (Respondent 1, 25/07/2019). In contrast, the BDAT was considered to be odour-free.

Household members said that the BDAT “is comfortable and even when you [are] sitting inside you even forget about all your problems” (Respondent 1, 03/05/2019). They stated that they were afraid to send their visitors to the UDDT, whereas they felt comfortable sending them to the BDAT because “it is a nice and a good toilet to have at home” (Respondent 2, 25/07/2019).

Respondent 2 (03/05/2019) highlighted the benefit of not having to empty the chamber of the UDDT. She spoke “on behalf of the mothers because they are the ones who were cleaning and emptying the UDDT, so they are on a break for now since we have this toilet”. As a result of this, the female family members named the toilet “the great break” (Respondent 1, 03/05/2019).

4.3. Recycling of water: a socio-technical transition

The BDAT system is designed to recycle water for toilet flushing and for handwashing, though the latter was not implemented in this field test due to safety concerns raised by members of the EFT platform.
The field testing of the BDAT therefore included the technical functioning of the recycling system and the household’s response to the use of recycled water in their household.

4.3.1. Water quality

The water quality was evaluated in terms of chemical composition (chemical oxygen demand, nitrogen species, phosphate), hygiene (pathogen indicators Escherichia coli and fecal coliforms, free chlorine concentration) and appearance (colour, turbidity, total suspended solids) as described in Reynaert et al. (2020) in detail.

The biological treatment of the water was stable throughout the testing. Removal of organics, nitrogen and phosphorus from the water was high (removal of 99.8% removal of the chemical oxygen demand, 95.7% of total nitrogen and 89.6% of phosphate). Pathogen indicators were generally absent in the treated water, with three exceptions where low concentrations of E. coli (3.1 and 1 most probable numbers (MPN)/100 mL) and total coliforms (56.5 MPN/100 mL) were detected. Free chlorine concentrations were around 0.05 mg/L when electrolysis was working, however, the electrolysis recirculation pump broke down on two occasions (see Table 1), resulting in the absence of residual chlorine in the water. Throughout the testing, the water always appeared clear to the human eye (average colour of 0 on a Platinum-Cobalt scale, turbidity of 0.37 ± 0.18 Nephelometric Turbidity Units, and 1.7 mg/L total suspended solids).

In the case of the BDAT, the household relied on and trusted the engineers that the water in the system was safe. Other than its appearance and possibly its smell, the household had no other way of determining the quality of the water and hence its safety.

4.3.2. Household response to using recycled water

Prior to the installation of BDAT, household members were not familiar with the term ‘recycled water’. Their responses to the questions about recycled water revealed that they had a low level of understanding of the concept, when it referred to the cleaning and re-use of water within a technical system. They used water from the river and potable municipal water, as well as the UDDT, and had hence not experienced technical services where water is recycled. After the term was explained to them, they stated that they would find it acceptable for recycled water to be used for flushing toilets, handwashing, and that they would encourage their children and their friends to utilise recycled water. However, these responses were not based on experience or an initial understanding of the concept of recycled water.

Household members stated that they would be unwilling to use recycled water for cooking, irrigating food crops, laundry, handwashing, bathing, showering and drinking; they were neutral about using it to wash cars; and they would be willing to use it for non-food crops and fire hydrants. These responses support the result that the household was not in favour of using recycled water widely, even though they had provided some support for it as a concept.

The household obtained water from the municipal ground tank in their garden, from collecting rainwater and from the nearby river. As the municipal supply was only 300 L per household per day and at times unreliable, water was perceived as a scarce and valuable resource. According to Respondent 1 (03/05/2019) “we think this toilet is a great help because at the moment we do not have water in our grey [ground] tank, and with this water since it is always there, we think it is good to save water in this way”. The respondents asked questions about the recycling process in the BDAT, as they wanted to know how it worked and where the feces and water went in the toilet so that it could be treated. They knew and understood that chemicals (i.e., the chlorine produced for disinfection) treated the water, but they requested information on the mechanics of how this worked. They believed the greatest risks of using recycled water are skin rashes and cholera, and felt the main benefit of having access to recycled water was that those who lived far from the river would have access to water.

5. Discussion

5.1. Position of the household in the history and geography of sanitation services in Durban

The household in which the testing of the BDAT took place is governed by both the eThekweni Municipality and the Qadi Traditional Authority. The position of the household in the periphery of the city has defined the type of sanitation the household has access to, based on the spatially differentiated service provision model, and the relationship the household has with the local state in terms of service provision (Sim et al., 2018).

The household does not engage regularly with the municipality over service delivery and hence a pattern of exceptionalism was established during the testing period. The household had engineers from the EFT and from Eawag monitoring and maintaining the system twice a week. In addition, they could report faults to both the CLO and the engineers, which ensured that any problems were quickly addressed.

This level of engagement is in contrast to normal practices, where households in peri-urban areas do not receive the same level of support or quick response time in relation to water and sanitation issues. As a result, household members have a high level of tolerance for systems that do not function well and they continue to use or adapt services when they do not meet their needs (Sutherland et al., 2019). This high level of tolerance and the position of the household in the less developed rural periphery, means that their expectations of service delivery, while aspiring to waterborne flush toilets, have been adjusted due to their context and their reality. The BDAT testing process therefore brought significant development benefits to the household, as it resulted in engagement between the household, the state and research institutions. This included the provision of an improved electrical system, which remained in the household after the prototype was removed, a new sanitation system that was tested for three months and removed, apart from its concrete slab which the household will use to support a new structure, and social learning around new sanitation systems and recycling. Household members valued the information provided on the BDAT as they stated that it increased their knowledge and therefore their ability to interact with the engineers and municipal officials. EWS provided training and posters for each household when the UDDTs were provided, but the household members indicated that the municipality had not engaged households in enough depth, when this form of sanitation was rolled out. Mkhize et al. (2017) revealed a need for increased community participation to address users’ perceptions, attitudes and behaviour concerning the UDDT. In contrast, the household had an ‘open door to the municipality’ during the testing of the BDAT and they were assured that the knowledge they contributed would be taken into account in the evaluation of the system. As a result, they expressed that they felt valued and included in the process of testing and developing new sanitation systems for the municipality (Respondent 1, 03/05/2019). This demonstrates the importance of adopting a participatory and integrated approach to sanitation delivery that takes into account the resources needed to ensure that beneficiaries have their voices heard during the design and implementation of new sanitation systems and that they are engaged in education processes about maintaining new systems.

Interestingly, the testing of the toilet produced narratives about the politics and inequality in service provision in South Africa. Neighbours associated the testing of the new sanitation system with the privilege and power of whiteness. They asked the household if they had joined the Democratic Alliance (DA), a political party in South Africa that is associated with whiteness, when they received the new sanitation system. According to Hunter (2019), “the association between whiteness and positive characteristics, including civilisation, freedom and modernity, was first highlighted by black writers including W.E. Du Bois, Frantz Fanon, and Steve Biko”. The impact of race on access to flush toilets and the presence of white engineers in under-developed black
5.2. Household response in relation to existing sanitation

While waterborne sanitation remains the preferred form of sanitation provision, evidence from the literature reveals interim improvement in sanitation from more cost-effective and water-efficient options, such as UDDTs or ventilated pit latrines (Currie et al., 2014). A study on the acceptance of UDDTs in Kimberley, South Africa, showed a high degree of dissatisfaction among the users, but also revealed that a higher level of acceptance could have been achieved if there had been more commitment from politicians and officials and active participation of the users in the decision-making process (Masebe and Osman, 2012).

The household response to the BDAT was shaped by their existing sanitation system. The household’s response to the UDDT is aligned with the results of a study conducted on user satisfaction of UDDTs, in which 71% of Mzinyathi residents use their UDDT every day, but 73% of residents were dissatisfied with this type of toilet (Sutherland et al., 2016). The main reasons for being dissatisfied were the shallowness of the UDDT vault below the toilet, which meant that the stored waste was close to the user of the toilet, the emptying process of the UDDT, the smell, the poor workmanship on the structure and the dysfunctional doors. The study revealed that respondents would like to have a flush toilet that they did not have to empty themselves.

The household members’ response to the BDAT system was very positive, mainly because it addressed the many challenges associated with UDDTs and it met the aspirational desires of the household. The BDAT created a private space where household members were happy to relax and spend time in comparison to the UDDT, which they used as quickly as possible. The use of a toilet as a space to spend time alone, engaging in personal activities such as thinking, taking a few minutes away from other members of the household, or being on the phone, has been highlighted in all the testing of toilet prototypes on the EFT platform. This needs to be taken into account in the design and development of toilets. The on-site treatment of the waste, which meant that it was not exposed to the residents and took place without needing human effort to remove it, was considered to be an important and successful feature of the BDAT.

5.3. Social learning and the reframing of knowledge on water recycling

There is growing awareness across South Africa and in eThekwini Municipality about the scarcity of water and the need to conserve it. The household members were aware of the country’s water shortages, particularly in relation to drought, and they had experienced water shortages in their own household due to unreliable water provision. The testing process revealed their knowledge of water scarcity. It also served to reframe their knowledge on the recycling of water. While they understood that water could be obtained from numerous sources and that households used their own systems to clean river water for use, they were not aware of technical sanitation systems that recycled water. They supported this concept, once they became aware of it through their engagement with the prototype, the engineers and the social scientists, and revealed who they would trust in relation to ensuring that the systems being used were safe and reliable.

The household was aware of the difficulty of providing sufficient water for conventional flush toilets, which is aligned with other studies of water use in the Global South. For example, a survey focused on potable water reuse in Durban found that 54% of respondents recognised water as a scarce resource (33% did not believe that water is scarce and 13% did not have an opinion) (Wilson and Pfaff, 2008). Contrary to a common assumption that people in developing countries are less concerned about environmental quality, as they prioritise other needs, environmental aspects are important social concerns around the provision of sanitation (Santos et al., 2011). The household appreciated the water-flush toilet in the BDAT, but also reflected on the value of the system, as the flushing did not increase water demand, which they were concerned about. Household members stated in the pre-installation questionnaire that they would only be able to provide input on the type of education and communication required to promote recycling of water through new technologies, once the system had been tested in their household. After the testing of the BDAT, household members were willing to engage in and share knowledge about the education and communication processes required to support the uptake of the technology in their neighbourhood, as they had learnt through the process of experimentation. Conducting further research on the social learning and capacity building that takes place both at the household and in the wider community through Td research has emerged as being of value in the testing of the BDAT.

5.4. Participation in the transdisciplinary research process

The willingness of households to engage with scientific knowledge and to understand the systems they are testing is evident across the EFT platform in Durban. The desire to know how the systems work, in scientific terms, was also apparent in the BDAT testing process. Household members explained that they wanted to know how the system worked, and what engineering processes ensured its functionality and safety, before it was installed in their household. This reveals the high level of engagement of the household with the system; they did not want to be passive recipients or users of the new technology, but they actively wanted to participate in the co-production of knowledge and the assessment of the system. This meant that they required detailed knowledge on the science and engineering of how it functioned. This supports adopting a Td approach, where science is not only transferred in to the Td space by scientists and engineers, to address problems in reality, but that the sharing and co-production of knowledge by multiple actors in the EFT platform (see Fig. 4) is central to the research process. This will ensure more just socio-technical transitions.

The study revealed that the Td research outcomes were made more meaningful as a result of the relatively long testing duration; the multi-layered social assessment process which ensured the co-production of knowledge; the ongoing communication between the household and the EFT team: the continual ‘going back to check up’ approach of the engineers and social scientists; the ongoing engagement and information exchange between the scientists and engineers engaged in the project through regular meetings; and respect for both state and traditional authority protocols required for engaging with community members. The household did not contain any men older than 18 years, which was a limitation of the study, as the urinal was only tested by younger males. Choosing a household with both older males and females would be useful in future studies.

6. Conclusions

The BDAT functioned well and had a high level of social acceptance. The flushing, cleanliness and odour-free nature of the sanitation technology, its functionality, the household’s previous sanitation experience, their experience with and understanding of water scarcity, and the way the testing process connected household members on an ongoing basis to the state, are the main factors underpinning their positive responses.

There were a few incidents where the toilet malfunctioned, but these problems were addressed quickly by the engineering team. This raises the issue of good governance, management systems and accountability, if new sanitation technologies are to be delivered at scale. The
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.

Acknowledgements

This publication is based on research funded by the Bill & Melinda Gates Foundation (grant numbers OPP1176460 and OPP170678). We would like to thank eThekwini Municipality (Water and Sanitation Unit), Khatiya Projects and Bonginkosi Ndawonde at PRG/UKZN for providing on-the-ground support. We are also grateful to Lotte Kristofertisch and Harald Gründl from EEO for discussions on the toilet design approach, to Pius Krütt from ETHZ for valuable input on transdisciplinary research, and to Chris Buckley at PRG/UKZN and Nadja Contzen at Eawag for helpful feedback on the manuscript. Our special thanks go to the Dhlaminis who participated in this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.143284.

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