Science of the Total Environment 576 (2017) 264–272

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Early testing of new sanitation technology for urban slums: The case of the Blue Diversion Toilet

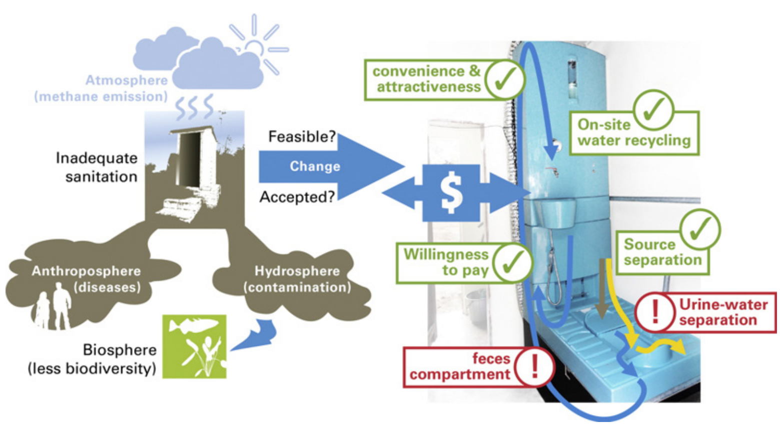
Robert Tobias [a,*,1], Mark O'Keefe [a,2], Rahel Künzle [a], Heiko Gebauer [a], Harald Gründl [b], Eberhard Morgenroth [a,c], Wouter Pronk [a], Tove A. Larsen [a]

[a] Eawag, P.O. Box 611, 8600 Dübendorf, Switzerland
[b] EOOS Design, Zelinkagasse 2/6, 1010 Vienna, Austria
[c] ETH Zürich, Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland

HIGHLIGHTS

- Inadequate sanitation in urban slums is a threat to the total environment.
- Zero-emission toilet with recycling of wash water tested in Slum in Kampala, Uganda.
- Approach for valid & representative acceptance estimate with only one working model.
- Source separation & on-site water recycling is feasible and has market potential.
- Separating urine from water and the feces compartment pose challenges to the design.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 July 2016
Received in revised form 6 October 2016
Accepted 8 October 2016
Available online 24 October 2016

Editor: Simon Pollard

Keywords:
Urine diversion
Gravity-driven membrane bioreactor
Innovation
Usability
Acceptance
Low-income countries

ABSTRACT

The toilets used most in informal urban settlements have detrimental consequences for the environment and human health due to the lack of proper collection and treatment of toilet waste. Concepts for safe, sustainable and affordable sanitation systems exist, but their feasibility and acceptance have to be investigated at an early stage of development, which is difficult due to the high costs of building working models. In this paper, we present an approach to estimate acceptance in a valid and representative form with only one working model, and apply it to test an innovative zero-emission toilet with recycling of wash water. Four basic principles were specified for investigation and nine hypotheses formulated to test the feasibility and acceptance of these principles: source separation of urine and feces with subsequent collection for resource recovery; provision of wash water in a separate cycle with on-site recovery through a membrane bioreactor; a convenient and attractive overall design; and a financially sustainable business plan. In Kampala (Uganda), in 2013, data was collected from 22 regular users, 308 one-time users and a representative sample of 1538 participants. Qualitative data was collected from the users, who evaluated their likes, perceived benefits, social norms and expected ease of use based on verbal and visual information. Most of the hypotheses were confirmed, indicating the feasibility and acceptance of

Abbreviations: BDT, Blue Diversion Toilet; BMGF, Bill & Melinda Gates Foundation; MBR, membrane bioReactor; RTTC, Reinvent The Toilet Challenge; SI, supporting information; UDDT, Urine Diverting Dry Toilet; UGX, Uganda Shilling (currency used in Uganda).

* Corresponding author.
E-mail address: robert.tobias@uzh.ch (R. Tobias).
[1] University of Zurich, Binzmühlestrasse 14/15, 8050 Zurich, Switzerland
[2] Sanergy, Nairobi, Kenya

http://dx.doi.org/10.1016/j.scitotenv.2016.10.057

the basic principles. Source separation and on-site water recovery were found to be feasible and accepted, provided users can be convinced that the emptying service and water recovery process work reliably. In the survey, the toilet was evaluated favorably and 51% of the participants agreed to be placed on a bogus waiting list. However, some design challenges were revealed, such as the size of the toilet, hiding feces from view and improving the separation of urine and water.

1. Introduction

Worldwide, 2.4 billion people live without adequate sanitation (United Nations, 2015), a situation which has grave implications for public health and the environment. Diarrhea – mostly caused by unsafe sanitation and drinking water, combined with a lack of hand-washing with soap – kills about 760,000 children under five annually (World Health Organization, 2013). Particularly in the informal urban areas of low-income countries, it has proved extremely difficult to develop adequate sanitation systems that safely contain, transport, treat and dispose or reuse waste.

The typical toilet technology in urban slums consists of pit latrines (Jenkins et al., 2015): this has a number of negative consequences for public health as well as the environment. Emptying is often unhygienic and expensive, leading to dangerous practices of overfilling the pit and/or flooding it out (Jenkins et al., 2015). Ground water contamination is frequent (Graham and Polizzotto, 2013), and in many cases the fecal sludge is dumped into water courses, with devastating effects on surface water quality (Semiyaga et al., 2015). Increasing eutrophication in low and middle income countries, to a large degree caused by the nutrients contained in human excreta from cities (Nyenje et al., 2010), is raising awareness that the sanitation crisis is detrimental not only to public health, but also to the environment. This is reflected in the more comprehensive Post Millennium Development Goals for sanitation, which also involve water pollution control and resource recovery (UN Water, 2015), and are discussed in more detail in Larsen et al. (2016).

Whereas the effects of pit latrines on water quality are well documented (see above), only little information is available on the possible effects on climate. However, with close to two billion people relying on this technology (Graham and Polizzotto, 2013), methane emissions could be substantial. Yearly methane emissions are estimated to be around 1 kg per person from the anaerobic processes in pit latrines (Reid et al., 2014), corresponding to about 2% of the methane emissions from an average person.

In urban slums, it is not an easy task to find alternatives to pit latrines, and more attractive on-site technologies are often considered merely a temporary solution until off-site sanitation can be afforded in the slum (Kerstens et al., 2016). The low-cost sewers suggested in (Paterson et al., 2007) as the most appropriate sanitation technology for low income, high-density urban areas fail to offer adequate solutions for water provision and water pollution control. Katukiza et al. (2010) identified the Urine Diverting Dry Toilet (UDDT) and biogas latrines as possible good solutions for a specific urban slum in Uganda, but point out the lack of acceptance of these simple technologies. Furthermore, neither solution represents an integrated option for hand-washing, a necessary element for making any sanitation solution truly hygienic (Greenland et al., 2013).

In 2011, the Bill & Melinda Gates Foundation (BMGF) challenged a number of research institutions to find more complete sanitation solutions for the urban poor living on less than US$2 a day (Reinvent The Toilet Challenge, [RTTC]) (Anonymous, 2011). The BMGF called for high user comfort, zero emissions to the environment, on-site solutions for resource recovery, and low costs of US$0.05 per person per day. The costs are comparable to the lifecycle costs of community-based sanitation solutions with simple anaerobic technologies reported for Indonesia by Kerstens et al. (2015) (US$0.03/p/day), but should provide significantly more comfort for the users. This goal should be achievable in a typical slum area with no grid infrastructure (no electricity, piped water or sewers).

The Blue Diversion Toilet (BDT) was developed as part of this program (Larsen et al., 2015). The BDT is essentially a UDDT as suggested by Katukiza et al. (2010), improved with a separate water cycle (the 'blue' diversion) for personal hygiene (hand-washing, anal cleansing, and menstrual hygiene) and flushing of the front compartment. It combines the simplicity of the water pollution control and resource recovery of a UDDT with the hygienic advantages of an integrated hand-washing facility. Zero emission and grid independence are ensured via internal water treatment and recycling (Künzle et al., 2015).

The BDT is based on the Sustainability Development Goals (SDG), and helps fulfill the requirements described primarily in SDG 6: providing safe sanitation with hand washing with a special emphasis on menstrual hygiene (SDG 6.2), saving water through a closed water cycle (SDG 6.4), and preventing water pollution through the zero-emission principle (SDG 6.3). As far as possible, the BDT concept follows the principle of SDG 11 (sustainable cities): Most parts of the toilet can be produced locally (the plastic parts, for instance, by the simple process of rotational molding), and the service and resource recovery concept provides local job opportunities.

Resource recovery is the basic concept of ecological sanitation leading to highly efficient water pollution control because the pollutants are turned into valuable products instead of being discharged to the environment. On average, the yearly excretion of a human being amounts to 22 kg COD (organic matter) with an energy content of 270 MJ, 3.7 kg nitrogen (N) and 0.7 kg phosphorus (P). The BDT concept allows >95% of these resources to be recovered.

These ambitious sustainability goals can only be fulfilled by a specific design that differs considerably from that of the typical aspirational flush toilet. This calls for co-design with potential users. Furthermore, including a water cycle imposes costs on users and developers alike, and these will only be justifiable if the availability of clean water helps transform the rather unattractive UDDT into an aspirational product. While established market research techniques are well suited for testing the development of incremental innovations to an already existing product (Leifer et al., 2000; Lynn et al., 1996), it is a greater challenge to assess more fundamental innovations (Lettl, 2007; O'Connor and McDermott, 2004). Most importantly, it is difficult for potential users to imagine a product that does not yet exist – something which is required in order to provide valid evaluations (Veryzer, 1998).

A framework for including users in the development of such innovations in the medical-technology sector (Lettl, 2007) includes three aspects: (1) identification of the development stage and purpose for engaging with users; (2) close interaction with competent "lead users" who are likely to purchase the product; and (3) ensuring that many users interact with the product. Our study examines the development phase (i.e. after ideation, but before market testing), and the purpose of engaging with users is to test the feasibility and acceptance of the basic design principles. To interact with lead users, it is necessary to test the toilet in the target area (i.e. urban slums). The third aspect is more problematic in this case. For practical reasons, only one working model of the BDT could be produced, which limited the number of people who could test it.

We propose an approach for testing fundamental innovations at an early stage of development (i.e. long before the final product is