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Assessing clogging of laminated hydrophobic membrane during fecal sludge drying

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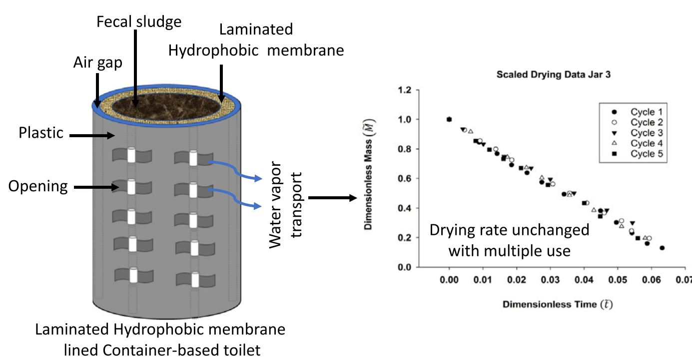
HIGHLIGHTS

- A laminated hydrophobic membrane permitted significant fecal sludge (FS) drying over 5 cycles.
- Particulate accumulation from FS between cycles occurred but did not reduce drying.
- FS drying rate decreased below a critical moisture content, when water activity <1.
- FS drying was 10–30% slower than water evaporation through laminated hydrophobic membrane.

GRAPHICAL ABSTRACT



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ABSTRACT

A new sanitation technology has been proposed in which a laminated hydrophobic membrane contains and enhances drying of fecal sludge in a toilet, with particular focus on application to urban regions of low-income countries. The proposed technology uses a laminated hydrophobic membrane liner as an integral component of container-based sanitation systems. The focus of this study is to quantitatively evaluate the laminate's clogging after repeated use, which will affect replacement interval and might limit the laminate's application in container-based toilets. The membrane of the laminated hydrophobic membrane used in this process is hydrophobic and only allows vapor transport. Drying of water vapor using the laminated hydrophobic membrane occurs due to moderate temperature or humidity gradients, while other constituents such as aqueous dissolved solutes of fecal sludge are retained. Controlled laboratory experiments evaluated repeated use of a laminated hydrophobic membrane for fecal sludge drying, with mild brushing/rinsing of the laminate between each application. Drying occurred at a constant rate as long as the fecal sludge moisture content exceeded 11.6 (g/g), below which water activity <1. Over five drying cycles, at a significance level of $\alpha = 0.05$ the dimensionless drying rate in the constant-rate period was not reduced. While scanning electron microscopy and energy dispersive X-ray analyses of used laminated hydrophobic membrane showed deposition of fecal sludge on the inner fabric of the laminate, particulate accumulation was never sufficient to alter the fecal sludge drying rate. Experiments with only water indicated that the fecal sludge increased the effective diffusion length through the laminate by 10–30%. These data demonstrate that clogging of the laminated hydrophobic membrane is minor over five cycles of fecal sludge drying with mild rinsing between cycles, indicating that use of the laminate may be feasible in many field applications.

1. Introduction

According to the World Health Organization and UNICEF only 63% of the world's population has access to improved sanitation facilities that

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eliminate human contact with fecal sludge (FS) (WHO, 2013). FS is a combination of human feces, urine and blackwater, and may contain greywater (Strande et al., 2014). An estimated 2.8 billion people live without adequate sanitation, 85% of whom use unimproved sanitation facilities where hygienic separation of FS from human contact is not ensured. Unimproved sanitation systems include unlined pit latrines, while approximately 15% of those living without adequate sanitation practice open-defecation (Katukiza et al., 2012; Mara et al., 2010; UNDP, 2006). Inadequate sanitation systems in urban slums are a factor causing diarrhea and bacterial infections, which result in 1.5 million child deaths per year (Mara et al., 2010; Prüss-Üstün et al., 2008; Sidhu and Toze, 2009; WHO, 2013). The lack of appropriate sanitation technologies is one reason why open defection is widely practiced in low-income countries (WHO, 2013).

In urban slums, pit latrines are a widely-used sanitation technology (Chaggu et al., 2002; Howard et al., 2003; Kulabago et al., 2009; Thye et al., 2011; WHO, 2013). Pit latrines consist of a hole in the ground where FS is collected, with fluids infiltrating from the hole into the subsurface. In 2013, an estimated 1.8 billion people were reported to utilize pit latrines as the primary means of FS collection (Graham and Polizzotto, 2013). Even if pit latrines are properly constructed, operated, maintained and emptied to prevent solids buildup, they often result in environmental and health risks in urban slums (Howard et al., 2003; Kulabago et al., 2009). Firstly, pit latrines are usually emptied manually due to the narrow streets in dense urban slums that make them inaccessible to waste removal trucks. This emptying practice may expose laborers and community residents to FS pathogens and parasites (Russel et al., 2015). Secondly, the aqueous phase of FS collected in pit latrines contains pathogens, parasites and organic contaminants that will infiltrate into the ground and may contaminate groundwater. Finally, pit latrines may overflow during the rainy season with devastating effects on surface water quality (UNDP, 2006). Studies evaluating the health and environmental risks of pit latrines have identified human exposure to microbial and chemical contamination as the main concern for their application (Banerjee, 2011; Dzwairo et al., 2006; Graham and Polizzotto, 2013; Pujari et al., 2012; Verheyen et al., 2009; Vinger et al., 2012; Zingoni et al., 2005).

Although alternatives to pit latrines have been proposed in the developing world in the last decade, finding alternatives in urban slums is challenging due to the lack of money, space, and access, as well as a sense of ownership that is often absent in public facilities (Tobias et al., 2017). Biogas latrines and the Urine Diverting Dry Toilet (UDDT) have been suggested as replacements to pit latrines in urban areas (Katukiza et al., 2010; Katukiza et al., 2012). Biogas latrines utilize anaerobic digestion to produce biogas from FS, which is stored under a fixed dome. The application of biogas latrines has faced some difficulties, though, which include availability of trained personnel for process control, the occurrence of pathogens in the digestate, and high investment costs (Katukiza et al., 2012). UDDTs have faced acceptability issues in some urban slums (Katukiza et al., 2010).

As an alternative to biogas latrines and standard UDDTs, a container-based sanitation (CBS) system was recently proposed for use in urban slum areas where constructing sewerage is infeasible (Tilmans et al., 2015). In a CBS system, FS is collected in a sealable container that is then transported to a treatment facility, emptied, and returned and reused for FS collection. Many CBS systems may employ urine-diverting toilets, and thus might be considered a type of UDDT (Tilmans et al., 2015). Infrastructure associated with FS collection in a CBS system is typically situated above ground, which reduces construction costs and the system's vulnerability to flooding. In a pilot-scale study in Haiti where the feasibility of CBS systems were evaluated, the main advantage of the CBS system was less human exposure to FS, malodor and insects, since FS was stored and transported in sealed containers (Tilmans et al., 2015). The CBS system had the advantage of 24-h accessibility (Russel et al., 2015), and users were sufficiently satisfied such that 71% planned to become paying subscribers after the completion of the free testing period (Russel et al., 2015). However, the pilot-scale study also found that the operational costs of the CBS system was approximately two to three times more than operational costs for large-scale conventional waterborne sewerage collection (Russel et al., 2015). Most of this additional cost was associated with labor for emptying containers. Since water is the major component of FS, a technology that lowers the moisture content of FS during CBS system usage will decrease the system's operational costs by reducing the frequency of emptying. Alternatively, such a technology would lower the weight of CBS containers and thus lower transportation costs, and likely costs associated with final disposal of FS.

To reduce labor costs of CBS systems, a low-cost and sustainable solution was recently proposed (Marzooghi et al., 2017). In this approach, the membrane distillation process was adapted to biosolids drying in CBS system toilets by enclosing biosolids in a laminated hydrophobic membrane; the laminated hydrophobic membrane allows biosolids drying while preventing transport of aqueous dissolved solutes from biosolids. This characteristic depends on the hydrophobicity and pore structure of the laminated hydrophobic membranes (Marzooghi et al., 2017). The mass transfer of water vapor across a laminate is analogous to membrane distillation in which a vapor pressure gradient is the driving force for water vapor transport. While in membrane distillation the temperature difference between the feed and the permeate sides of the membrane controls the vapor pressure gradient (Curcio and Drioli, 2005; Souhaimi and Matsuura, 2011), when a laminated hydrophobic membrane encloses biosolids the drying rate is also controlled by the relative humidity (*RH*) of air external to the laminate. When the *RH* of external air is high and near 100%, the drying rate is reduced, but when *RH* is small it is enhanced.

To evaluate if lining toilets in CBS systems with laminated hydrophobic membranes might be efficacious, anaerobically digested sludge, i.e. biosolids, were enclosed in a commercially available laminated hydrophobic membrane, the GORE Wrap Cover Laminate (W.L. Gore & Associates, Inc., DE, USA). In a series of drying experiments, the biosolids' moisture content decreased from 97% to 12–30% while the transport of fecal coliforms across the laminated hydrophobic membrane was negligible. Moreover, the concentration of fecal coliforms in biosolids decreased three orders of magnitude during biosolids drying, which indicated fecal coliforms were inactivated during the drying process. At the end of the drying experiment, the concentration of fecal coliforms in biosolids met Class A and Class B requirements (USEPA, 2002).

While Marzooghi et al. (2017)'s results indicate that laminated hydrophobic membranes enhance biosolids drying and thus could reduce the frequency of toilet emptying in CBS systems, there are three unanswered questions regarding the application of this technology in a CBS sanitation system. First, Marzooghi et al. (2017) conducted their experiments using anaerobically digested biosolids, but will waste drying be different for FS since the chemical, physical and biological characteristics of FS differ for biosolids? For example, organic matter, total solids, ammonium, and helminth egg concentrations in FS are typically a factor of ten or a hundred larger than in biosolids from wastewater sludge (Strande et al., 2014). The dissimilar composition of the aqueous phase in FS and biosolids may result in different water activities in these wastes and water vapor transfer rates across laminates during drying.

Second, will water vapor permeation through the laminated hydrophobic membrane change significantly with repeated use of a laminate given that the Marzooghi et al. (2017) study consisted of a single cycle of biosolids drying? FS contains large colloidal organic and inorganic compounds (Strande et al., 2014) that may accumulate on the fabric of a laminate, resulting in additional resistance to water vapor transport and lower water vapor transfer rate with repeated laminate use. If significant, such clogging would deteriorate performance of a CBS system and increase cost of operation, if frequent cleaning or laminate replacement is needed.

Finally, while Marzooghi et al. (2017) evaluated the GORE Wrap Cover laminate for biosolids' drying, might other laminated hydrophobic