BREATHABLE MEMBRANE ENCLOSURES FOR FAECAL SLUDGE STABILIZATION

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ABSTRACT

Breathable membranes are used in the process of membrane distillation to desalinate water. They are made of a hydrophobic material with pore spaces that only allow vapour transport. The objective of this research was to evaluate them for drying and stabilization of faecal and other sludges. A central feature of the membrane is that water vapour can be expelled due to a moderate temperature gradient. Other constituents, including both particulate and dissolved, are retained. In applying this principle to sludge, the heat from intrinsic biodegradation or from solar heat will gradually expel water vapour, to dry the sludge while preventing groundwater contamination. In order to utilize this concept with sanitation methods in rural areas, it was necessary to quantify the membrane's capability to pass water, as a specific flux rate which is dependent on temperature gradient and membrane type. Test methods were therefore developed to obtain the flux rates with either a vapour or aqueous phase across the membrane from the sludge. Flux measurements are reported with controlled temperature gradients between 0°C and 10°C. Applying only a 2°C sludge-air difference across the membrane gives low moisture content (over 90% solid matter) and 99% removal of faecal coliform within 6 days. With the sludge separated from water by the membrane, and a 2°C sludge-water difference, the removal of water is slower, but 99% faecal coliform die-off was attained within 21 days while 2/3 of the moisture is removed.

Keywords: LATRINE, PRIVY, OUTHOUSE, HYDROPHOBIC, DRYING, COLIFORM.

INTRODUCTION

Waterless pit toilets (privies) are used in developing areas worldwide, although there are important drawbacks to their use (Mihelcic et al., 2009). Most important is the possibility of releasing pathogens or parasites through subsurface transport to nearby sources of drinking water (Cairncross and Feachem, 1993). Privies that must be emptied frequently also expose sanitation workers to health risks because the faecal sludge has not been adequately stabilized. An inexpensive modification to existing pit toilets to alleviate these problems would thus be desirable.

Breathable membranes are plastic materials that, due to their hydrophobic properties, do not allow passage of liquid water, or the contaminants in the water. However, they do allow water vapour to pass. This allows water purification, because water vapour can be driven across the membrane by a temperature difference. Even a small temperature difference can cause this vapour transport: for example, breathable fabrics prevent rain from penetrating a garment, but allow perspired moisture to exit due to body heat. Water can be distilled by this same means, and there is a growing literature on the "membrane distillation" process for desalination (e.g. Curcio & Drioli 2005). In addition to salt removal, membrane distillation also effectively excludes dissolved and particulate impurities.

These membranes might be useful beyond the production of distilled water. In this research, the objective was to determine if breathable membranes might be used as a latrine pit enclosure, to protect surrounding groundwater or floodwaters from contamination, while allowing faecal sludge to condense and stabilize. The membrane m be used under, around, or perhaps over the faecal material (as in a composting process) to improve the drying and thus disinfection of the material. If the faecal sludge warms as it decomposes—or if solar or above-ground warmth is provided—this which will act to drive water, and only water, out of the sludge through the membrane. Drying, combined with the release of ammonia as a breakdown product, inactivates pathogens in sludges, so that the material can be more safely removed from the modified latrine.

The breathable membrane is unlike either the conventional membranes used for water filtration or ultrafiltration, or the membranes used in geotextiles for dewatering. These membrane types permit the passage of liquid water, and thus contaminants of any size up to their pore dimensions, and also rely on pressure to force the filtration process. Instead, a breathable membrane has pores that fill only with air or water vapour, because the material is hydrophobic (specifically, it has a high contact angle which makes it non-wetting). Temperature, rather than pressure, drives the water vapour through the pores, in the direction of warmer temperature to cooler due to differing vapour pressures. Intensive processes, like desalination by membrane distillation, demand a temperature difference of at least 10-20°C, but a slower, passive system for faecal sludge drying could utilize lesser temperature gradients.

A key difference between the breathable membrane and other membrane types is the susceptibility to fouling or scaling. When material deposits on a conventional membrane by these mechanisms, they eventually block the passage of water. Bench-scale desalination tests, including electron microscopy, have shown that the hydrophobicity of a breathable membrane mitigates such deposition, so that water passage, or flux, is maintained for many thousands of hours. It was thus hypothesized that this resistance to fouling might extend to use in contact with faecal sludge.

Experiments were designed to measure the rate of water flux through the breathable membrane under two conditions. In both, one side of the membrane is directly in contact with the sludge. Water vapour is released through the membrane, so the sludge's moisture content decreases, and its solids content increases. It might be expected that the driest sludge would accumulate adjacent to the membrane and retard the flux, so some experiments included mixing on this side of the membrane. The temperature of the sludge is maintained at a constant value, and monitored by a thermocouple placed adjacent to the membrane in the sludge compartment.

The other side of the membrane, if used as a pit toilet enclosure, might be in contact with either air or water. If the pit is only within the unsaturated zone of the surrounding soil, the air would be within its porous volume. The membrane might also cover upper sludge surfaces and be in direct contact with air. However, if the pit descends into a zone of soil saturation, the membrane would contact water within the porous volume of the soil. In some applications, such as flooding or tidal areas, the membrane might be in contact with free water. In general, it might be expected that some fraction of a membrane enclosure could be in contact with air, and the remainder with water.

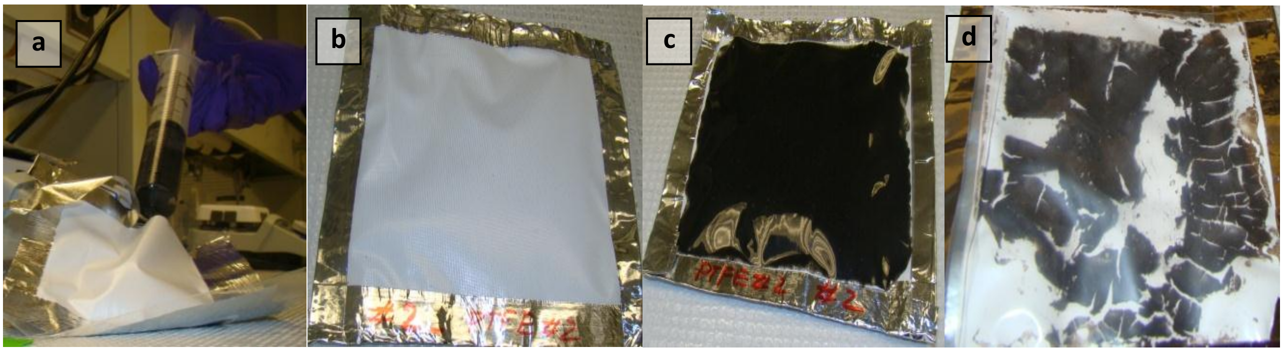

Figure 1. a: Injecting sludge into PTFE membrane covered enclosure. b: Sludge isolated by the membrane. c: Initial sludge appearance from back side of the enclosure (thickness: 1cm). d: Dried sludge after 3.9 days with a 2 C difference between inside and outside of the enclosure.

The simpler experimental simulation was with sludge on one side of the membrane, and air on the other. These measurements were performed using a membrane "envelope" with one side made of the breathable membrane and one of impermeable polyethylene plastic. The latter side was placed on a precision hot plate or water bath at 0, 2, or 10 degrees C above ambient temperature. The envelope was weighed periodically to track moisture loss. Figure 1 shows the use of this method with a membrane area of 10 cm x 10 cm, filled initially with 100 mL of anaerobically digested sludge.

With water opposite the sludge, a dual chamber device was required with temperature control on both sides. The configuration, shown in Figure2, includes two flanged glass cylinders, each with a diameter of 13 cm. The lower cylinder is 13 cm in depth with one end sealed. The upper cylinder has both ends open with a length of 21 cm. The two compartments are connected using a horseshoe clamp. Membranes are positioned between the two flanges, and the temperature gradient is achieved by controlled heating and cooling of the upper and lower compartments respectively. The lower compartment is immersed in a water bath cooled by a refrigerated circulator, with additional cooling potential provided by a copper coil heat exchanger in the lower cylinder. Cold water from the same refrigerated circulator flows through the copper coil. The temperature in the upper cylinder is elevated by the use of heating tape around the outer cylinder wall. A temperature gradient can be maintained within ± 1 C using thermocouples on both sides of the membrane, providing input to a proportional temperature controller.

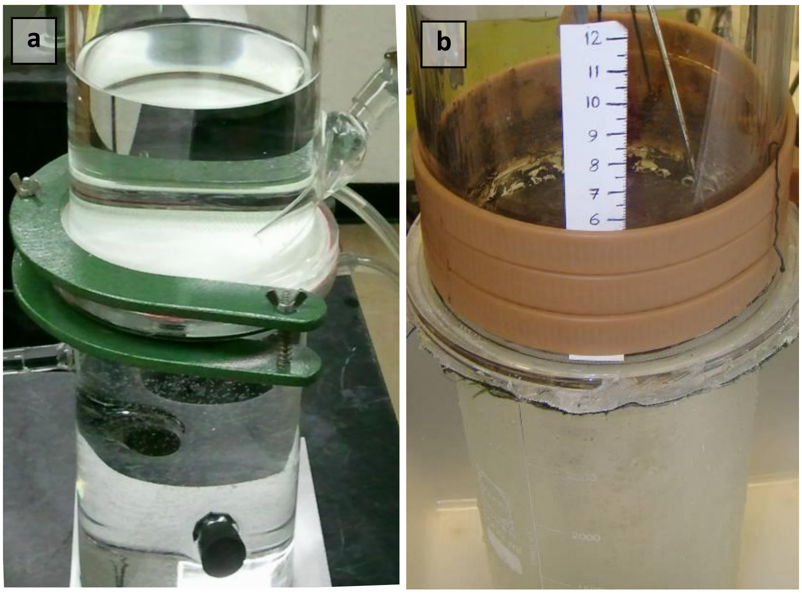

Figure 2. Testing for water vapour flux between sludge and water. a: apparatus assembled for control test with water. b: unclamped apparatus with heat tape, depth scale, thermocouple, and dried sludge visible after experiment.

This apparatus does not allow weighing of the dying sludge for quantification of drying during the experiment. Instead, the original solids concentration was combined with the measured depth and volume loss over time to calculate solids concentrations, which were then checked against the measured solids at completion.

During drying, samples were taken for faecal coliform counts using the EPA Method 1680 multiple tube fermentation procedure (USEPA, 2002). This method uses lauryl tryptose broth (LTB) and EC medium as the presumptive and confirmation media respectively. *E. coli* (ATCC # 25922) was used as the positive control for LTB and EC medium, while *Enterobacter aerogenes* (ATCC # 13048)and *Pseudomonas* (ATCC # 27853) were employed as the negative controls for EC and LTB respectively. Phosphate buffered dilution water (from autoclaved DI water) was tested for faecal coliform as the control blank.

RESULTS

Our results are only lab scale so far, but surprisingly successful. Figure 3 shows that the drying rate with membrane enclosure is not as fast as without the membrane, but that complete moisture loss occurs within a few days with only a 2 degree temperature difference. A lower temperature gradient is expected in a latrine pit, but a much longer drying time is also acceptable in this context. Although not shown, over 99% removal of faecal coliform was also attained in this drying period. Figure 4 suggests that a greater temperature gradient does increase the drying rate. The increase is not as significant in this experiment as in others, but the results again show complete drying within a few days.

A latrine pit may be in contact with unsaturated soil, making the results in Figures 3 and 4 relevant. If in contact with saturated soil or flooded areas, then the membrane will separate the sludge from water. Experiments to characterize this situation are exemplified by Figures 5 and 6. With the sludge separated from *water* by the membrane, and a 2°C sludge-*water* difference, the removal of water is slower, but 2/3 of the moisture is removed within 21 days as shown by the mass decrease in Figure 5.

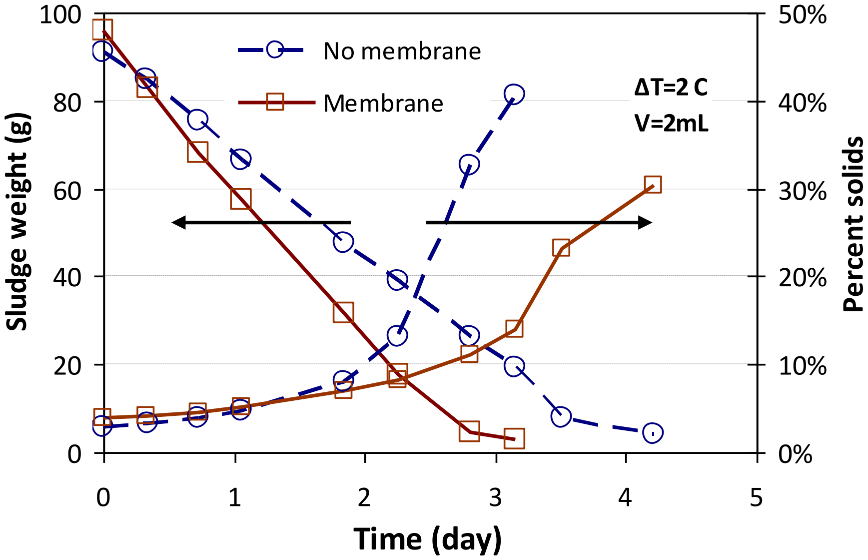

Figure 3. Changes in sludge weight and percent solids with and without membrane enclosure. PTFE membrane used. Initial volume 100 mL, temperature difference 2 deg. C, air exposure.

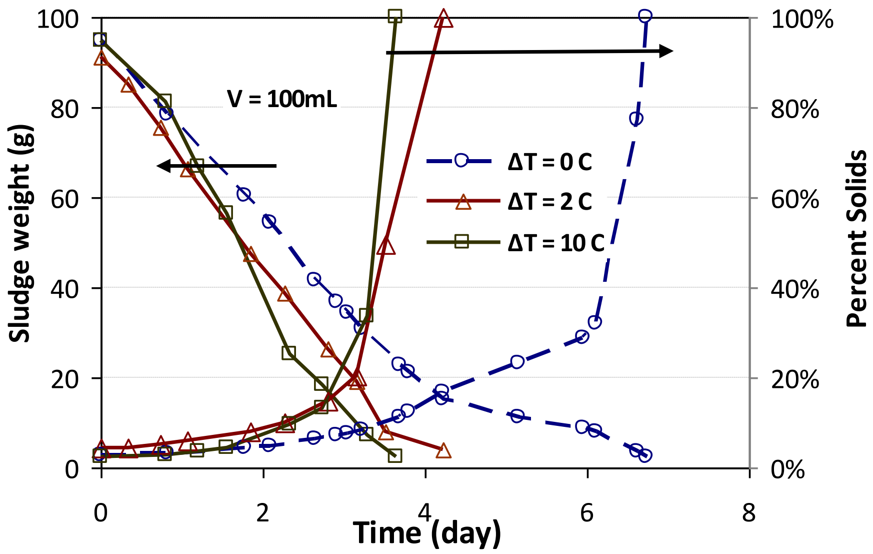

Figure 4. Changes in sludge weight and percent solids with PTFE membrane enclosure at three temperature differences. Initial volume 100 mL, air exposure

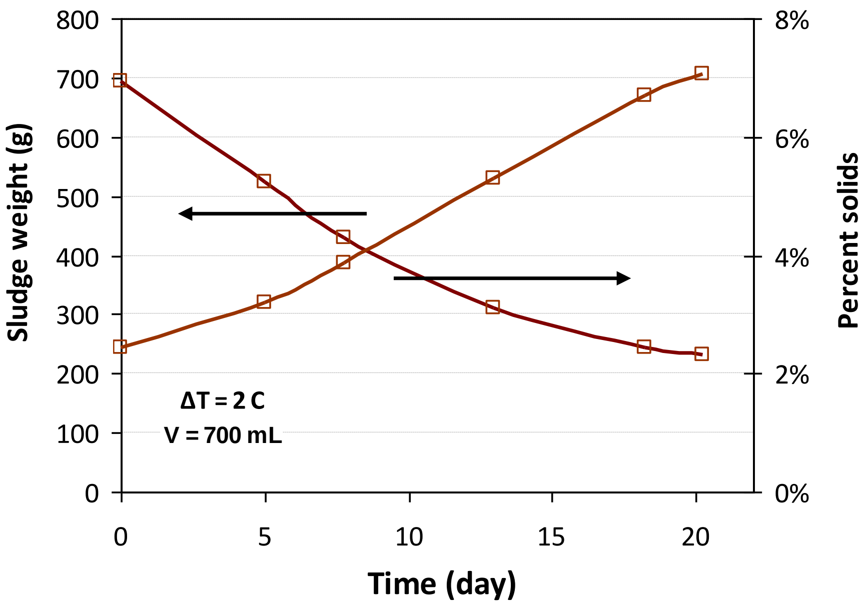

Figure 5. Changes in sludge weight and percent solids with PTFE membrane enclosure at three temperature differences. Initial volume 100 mL, temperature difference 2 deg. C, water exposure.

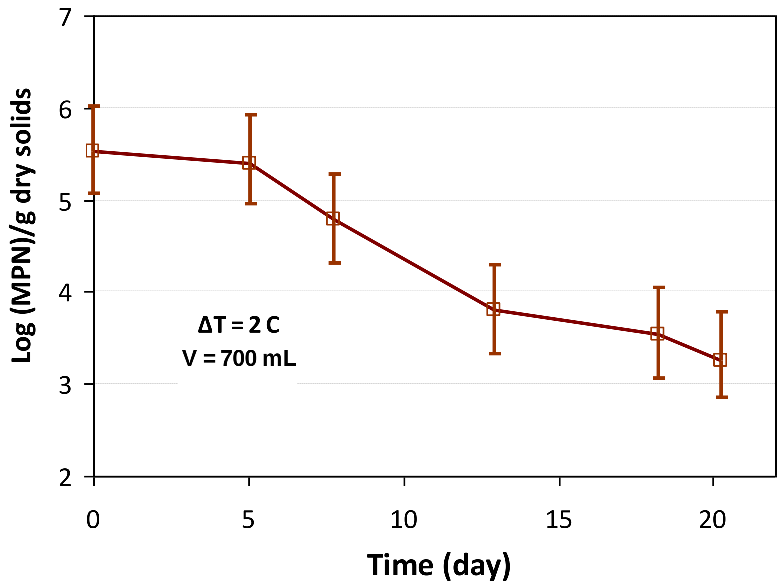

Figure 6. Changes in faecal coliform count during membrane drying, measured as most probable number (MPN), showing 95% confidence intervals.

In addition, over 99% faecal coliform die-off was attained, as shown in Figure 6 (with the faecal coliform amount indicated on a logarithmic scale). These results have been verified at other temperature differences and using different membrane types as well. In addition, faecal coliform measurements on the water side of the membrane have found no detectable faecal coliform. This demonstrates that the membrane acts as a protective barrier between the sludge and any surrounding media.

SCALE-UP

To predict the drying parameters in the scale-up design, a stagnant film model has been developed. The model predicts the molar drying rate (moles/ m^2 s) depending on temperature and the bulk vapour pressures across the membrane (equation (1)). This model gives quite reliable prediction of the rate of mass transfer when fluid flows through a phase boundary at steady state. The fluid (air) in immediate contact with the fixed surface can be said to be stagnant while there is a net motion of flowing fluid (vapour) away from the evaporating surface (Bird et al., 1960).

$$N_A = \frac{P}{R}\frac{D_{water-air@T_{ave}}}{T_{ave}}\frac{1}{\lambda}\ln(\frac{P-p_{A1}}{P-p_{A2}}) \quad [1]$$

where P is the total pressure of air and vapour and is assumed to be the atmospheric pressure in Pa, p_{A1} and p_{A2} are the partial pressures of water vapour inside and outside of the membrane in Pa respectively, T_{avg} is the average temperature of inside and outside of the membrane in Kelvins, and R is the ideal gas constant.

The stationary air creates a film resistance to the motion of vapour such that in the presence of the membrane, this resistance is considered as an overall resistance of the air filled inside the pores of the membrane and the membrane resistance itself. The parameter λ indicates the overall resistance. A helpful and simplifying result from this model is that the overall resistance was found not to be specific to the hydrophobic breathable membrane type (it can generally be quantified as 0.01 m), allowing general prediction of performance based on membrane area and temperature difference.

As long as the sludge contains free water (i.e. the dry base moisture content is over 30%), the relative humidity and therefore the vapour pressure inside the sludge are in a saturated state. In practice, the internal conditions will be determined by the extent of faecal sludge warming during biodegradation or by supply of external heat (e.g. passive solar) to control the temperature.

Typical pit latrine dimensions are presented in Figure 7 (Franceys, 1992).

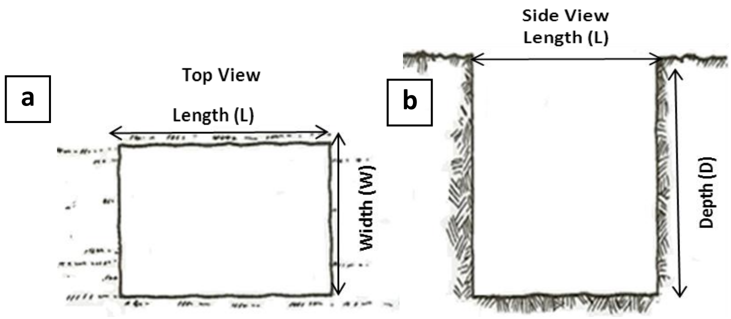

Figure 7. Typical pit latrine design criteria. L= 1.2m, W=1.1m, and D= 2.1 m. From (Franceys, 1992).

In an on-site sanitation system, as long as the water table is well below the pit latrine, the vapour pressure outside the pit latrine, p_{A2}, is equal to the vapour pressure of the soil (which is a function of temperature and relative humidity of the soil, here assumed to be 30 C and zero percent respectively).

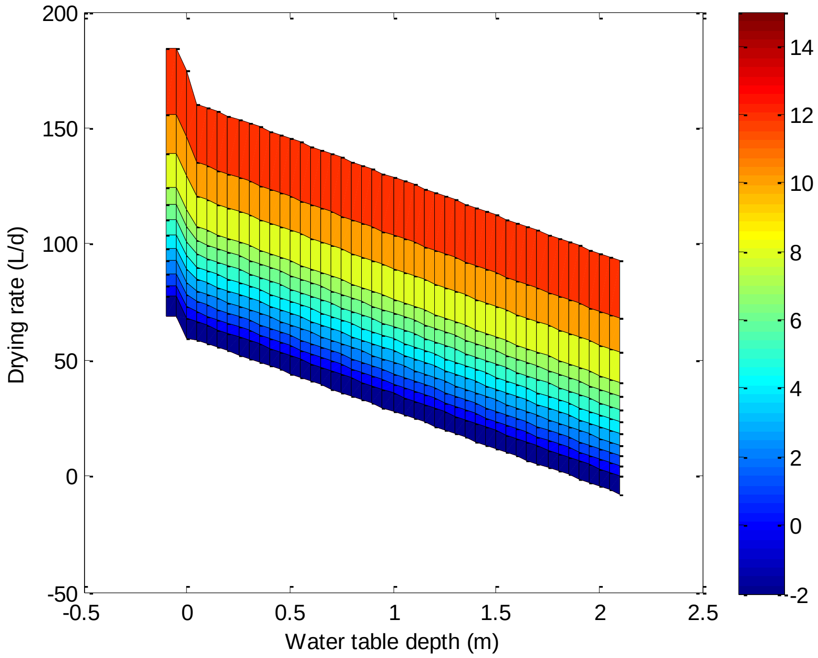

Figure 8. Drying rate profile at different water table depths and temperature gradients. The right column indicates the temperature gradients from low to high. Assumed latrine pit dimensions as in Figure 7.

If the membrane-enclosed pit is completely surrounded by water or fully saturated soil, a temperature gradient will still cause moisture loss from the faecal sludge, but this will be much more slowly, as shown by comparison of Figures 4 and 5. In some cases the pit may be partially within a water table, but partially above it, giving an intermediate rate of moisture loss. Figure 8 shows the drying rate as a function of the water table depth relative to the latrine and ground level, with coloured zones indicating temperature gradients from -2 ˚C to 14 ˚C.

This might be imagined as the effect on drying as a water table rises from below the pit. The membrane-lined walls of the pit latrine will start to become exposed to the saturated zone as the water table begins to elevate, then the relative humidity of outside area takes the value of 100%. This causes a considerable drop in the drying rate.

Predicting the vapour transfer rate in different modes of drying essentially enables us to estimate the capacity of the sanitation system. As a case in point, with application of a 2˚C temperature gradient when the water table is well below the pit latrine bottom, the moisture transfer is predicted to be 82.23 L/d. Taking a simplistic approach to the problem in the absence of local information, the system is assumed to receive 520 grams per person per day wet faeces in an African area (Franceys, 1992). Assuming 85 % moisture content (wet base) for the faeces (Chaggu, 2004), moisture input is calculated to be 0.44 liters per person per day. Expecting this amount of input allows approximately 186 people to utilize the on-site sanitation system daily.

CONCLUSIONS

1. The breathable membrane provides a significant rate of drying when serving as a barrier between sludge and air. The flux rate is slower than if the sludge is dried without a membrane, but the membrane serves as an effective barrier against pathogen transport.

2. Water flux, and the drying rate, are much slower when the membrane separates the sludge from water rather than air. However, the rate is sufficient to enable significant removal of water over time scales of relevance to latrine pits.

3. Rates of water removal predicted from our measurements suggest that a pit latrine lined with the breathable membrane can remove moisture at a rate sufficient to equal or exceed the likely loading from a population of several families.

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