Research Paper

Field demonstration of breathable laminate-lined container-based toilets in Kanpur, India

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ABSTRACT

Drying of fecal sludge (FS) enclosed in a breathable, hydrophobic membrane laminate was investigated in 208 and 40 L container-based toilet (CBS) systems referred to as Eco-Vapor toilets (EVTs). EVTs were constructed and pilot tested in four households in urban slums of Kanpur, India over a period of 2 years. The average moisture losses of 0.8 and 0.9 kg/day were observed in laminate-lined 208 L drums for Year 1 tests, and this *in situ* drying decreases disposal frequency by 8 days compared with CBS that do not allow FS drying. In Year 2, smaller EVTs with 40 L laminate-lined drums and waste segregation increased replacement time over conventional CBS by 45%, as opposed to the 19% increase observed in Year 1 tests. Despite its limitations, the stagnant film model using meteorological data predicted the mass-loss rate within 52 and 28% error for the 208 and 40 L drums, respectively.

Key words | breathable laminate, Eco-Vapor toilets, fecal sludge, stagnant film model

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HIGHLIGHTS

- Eco-Vapor toilets (EVTs) use breathable laminate-lined drums to store and dry fecal sludge.
- Drying rates of 40 L containers were higher than those of 208 L drums.
- *In situ* drying in the 40 L EVT extended the replacement time by 45%.
- The stagnant film model predicted mass-loss rates within 28% error for the 40 L EVT.

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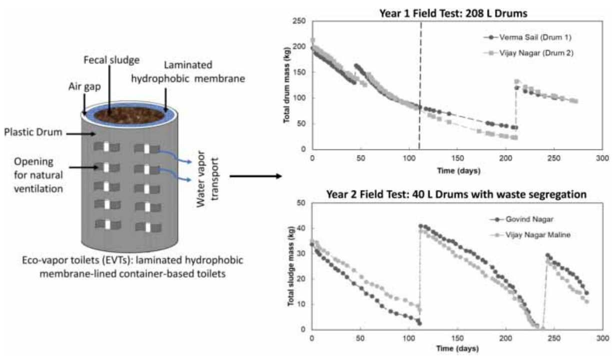
GRAPHICAL ABSTRACT



INTRODUCTION

In 2014, India launched the 'Clean India Mission' (Swachh Bharat Abhiyan) to comprehensively target urban and rural poor for improvement in their general quality of life. (Bakhshayesh *et al.* 2018, 2019) This program aimed at providing sanitation facilities to every household to eliminate the practice of open defecation in India while promoting the development of novel sanitation system solutions. According to the World Health Organization, 40% of the population still lacked basic sanitation services in 2017 (Bakhshayesh *et al.* 2019). A centralized sewerage system is too costly to build and operate in populated urban cities. Even popular decentralized sanitation systems, such as septic tanks and two-pit systems, have had limited success in the poor urban neighborhoods where the narrow, irregular street layouts prevent emptying of fecal sludge (FS) using vacuum trucks. Additionally, there is increasing evidence that the lack of adequate regulation of onsite systems compromises drinking water quality due to groundwater contamination (Central Pollution Control Board (CPCB) 2019; Dewhurst *et al.* 2019).

Container-based sanitation (CBS) has received increasing attention as a potential alternative to traditional decentralized systems (Ghosh 2016; Gensch *et al.* 2018). A CBS system is designed to collect and store excreta in sealable, removable containers that are transported and disposed once full (Graham & Polizzotto 2013). Since 2011, CBS toilet systems have been successfully applied in low-income settlements of Haiti, Ghana, Kenya, India and Peru (MacArthur *et al.* 2015; Gensch *et al.* 2018; Kolsky *et al.* 2019). CBS is low-cost, affordable, flexible and easy to adapt in densely populated areas with an overall simple management strategy for containment and easy disposal of FS (Marzooghi *et al.* 2017; Gensch *et al.* 2018).

Lining CBS with hydrophobic laminates can facilitate drying of FS at the point of collection and consequently increase the time between each disposal (Pradhan 2008; Orner & Mihelcic 2018). Laminated hydrophobic membranes such as Gore-Tex™ (W.L. Gore & Associates, Inc., DE, USA) and e-Vent™ (eVent fabrics, Lee's Summit, MO, USA) prevent water, pathogens and any dissolved ions in the FS to pass through the membrane (Pradhan 2008; Ratner 2009; Russel *et al.* 2015). On the other hand, water vapor can readily diffuse across the hydrophobic membrane resulting in increased concentrations of ions and solids inside the membrane enclosures (Ratner 2009; Russel *et al.* 2019).

This study examines the efficacy of a modified CBS for safely collecting and drying FS in urban slum households. These toilets, named the Eco-Vapor toilet (EVT), were proposed by Saxena *et al.* (2019a) as a potential sanitation solution for urban areas with limited space and technology options (Ratner 2009).

Four EVTs were piloted in different urban slum households of Kanpur, India over a period of 2 years. The objective was to assess the performance of these EVTs as a potential onsite sanitation system with *in situ* drying capability and to evaluate a previously developed drying rate model, the stagnant film model, with the field operation data. Once the drum was full, the FS was transported and disposed into a secondary unused laminate-lined drum, termed here as surrogate drums. These surrogate drums were made to the exact dimensions as their respective household EVT counterparts. Drying of FS from laminate-lined containers was tracked in the field using daily weight measurements. The daily average moisture loss was compared with the mass loss predicted by the stagnant film model. The social, financial and environmental aspects of these toilets are also important to access acceptability of this new technology, and hence these considerations will be published separately.

MATERIALS AND METHODS

Description of field sites

Field-testing of the EVTs was conducted at urban slums of Kanpur, India. Households in the urban slum areas of Verma Sail, Vijay Nagar, Govind Nagar and Vijay Nagar Maline were solicited for volunteers to participate in the pilot study. EVTs were constructed in one volunteer household each from Verma Sail (Drum 1) and Vijay Nagar (Drum 2) for Year 1 of field trial. In Year 2, EVTs were installed in Govind Nagar (Drum 3) and Vijay Nagar Maline (Drum 4).

Design of containers

All materials were purchased locally in Kanpur, India. A 208 L (55 gallon) high-density polyethylene (HDPE) drum (53.9 cm ID × 87 cm H) was strategically cut (Supplementary Material, Figure S1A) to allow natural ventilation around a laminate bag that lined the container (Russel *et al.* 2015). A secondary support plastic mesh was placed between the laminate bag and drum to protect the laminated hydrophobic membrane from the sharp edges of the drum and to enhance ventilation.

A 40 L HDPE drum (32 cm ID × 65 cm H) was also cut similar to the 208 L drum as outlined in Saxena *et al.* (2019b) (Supplementary Material, Figure S1B). The open areas created by the cut-outs were about 11 and 8% of the drum surface area for the 208 and 40 L drums, respectively. Similar to the 208 L drum, the same plastic mesh was used as secondary support and as a spacer between the laminate and the wall of the drum, which permitted ventilation within the container.

The laminate used for this study is the three-layered eVent laminate (see Supplementary Material, Section S1 for laminate properties). Similar to Saxena *et al.* (2019b), the laminate bag for the 208 L drum was designed from a single piece of fabric 264 cm long × 112 cm wide to minimize laminate wastage and reduce the total number of seams (Supplementary Material, Figure S2). Two seams (seams A and B in Supplementary Material, Figure S2) were stitched together.

For the 40 L drum, a smaller 1.0 m^2 piece of laminate was fitted inside the drum and clamped at the drum's mouth, forming an internal bag to collect FS. By lining the 40 L drum with a single piece of laminate that did not require cutting and sewing, the cost of sewing and potential leaks from seams were avoided.

Toilet construction and operation

The toilets were installed on the rooftops of the volunteers' homes (Figure 1). The cemented brick superstructure for the toilet was built around a metal frame. A SaTo pan system (Saxena *et al.* 2019a), which requires a smaller amount of wash water for flushing, was used as the toilet seat for the 208 L toilets (Year 1). The usage of these 208 L toilets was limited to four times per day with 1 L of wash water per use, amounting to a total loading rate of 5 kg/day. For the 40 L toilets (Year 2), an Eco-San squatting pan (Saxena *et al.* 2019b) was used, which contains three compartments for waste separation. The front compartment is designed for collecting urine, middle for fecal waste and back for cleansing water. Urine and wash water were collected in 50 L plastic containers, while the fecal matter was collected in a 40 L container lined with the breathable laminate. The source separation of waste with the new pan design assured that the loading rate of fecal matter per use would be lower. Similar to the 208 L drum EVTs, the usage of the 40 L drum EVTs was also limited to four times per day with 1 L of wash water per use (a loading rate of 1 kg/day). Each toilet was connected to a ventilation pipe fitted with a wind fan (Twister-100, Golden Engineering Co., India) to dissipate odors.

Figure 1 | EVT field setup in Kanpur, India for the (a) Year 1 field test with a laminate-lined 208 L (55 gallon) drum and (b) Year 2 field test with a laminate-lined 40 L drum and urine-diverting Eco-San pan. All toilets were fitted with a ventilation pipe with wind fan for odor control. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/washdev.2021.011.

Local sanitation contractors made weekly visits to the testing sites to monitor the FS depth in the drums. They also collected FS samples for the total solids analysis. When the collection drum filled up, the sludge was transferred to a secondary container for transport and disposal into a nearby sewer.

Data collection and analysis

For monitoring of daily average drying rates, four unused laminate-lined drums, termed as surrogate drums, were filled with FS collected from each respective household. Two each 208 and 40 L capacity surrogate drums were placed on individual weighing scales and read daily by a member of the field monitoring team. Surrogate drums were refilled twice with freshly collected FS from respective household toilets over an 8-month monitoring period.

The stagnant film model was used to predict FS drying rates with known laminate surface area, estimated sludge temperature and measured ambient RH and temperature (see Supplementary Material, Section S4). The laminate area in contact with sludge is termed as the wetted surface area (WSA). The WSA was calculated from the mass of the bulk liquid (see Supplementary Material, Section S4). A capillary rise was assumed to be negligible in the surrogate drums filled with FS and hence was not included in the WSA calculations. Sludge temperature was assumed to be equal to the daily average ambient temperature. The hourly and daily average climate data (ambient RH, temperature, wind speed and wind direction) were measured at the Air Quality Monitoring Station at Nehru Nagar, Kanpur, Uttar Pradesh (Tilmans *et al.* 2015).

Saxena *et al.* (2019b) conducted field experiments with the EVT prototypes (40 and 208 L drums), filled with tap water instead of FS, over a 11-day period and found that model-predicted error in the drying rate was ≤13% using 24-h average weather station data for temperature and relative humidity, measured water temperatures inside the laminate and pre-calculated effective diffusion lengths: $\lambda_{\text{Water}} = 1.38 \pm 0.01\text{SE} \times 10^{-2}$ m (SE = one standard error) and $\lambda_{\text{Water}} = 1.73 \pm 0.01\text{SE} \times 10^{-2}$ m for the 40 and 208 L drums, respectively (Russel *et al.* 2015). These λ values are measures of the resistance to moisture flux at the liquid–laminate interface. However, since the surrogate drums in these field tests contained FS instead of water, λ were corrected by a factor of

1.12 to account for the increased resistance associated with FS (Russel *et al.* 2015; Orner & Mihelcic 2018). Hence, effective diffusion lengths of $\lambda = 1.55 \times 10^{-2}$ and $\lambda = 1.94 \times 10^{-2}$ m were used for FS drying in breathable laminate-lined 40 and 208 L drums, respectively.

Finally, to assess the influence of the laminate on the frequency of toilet emptying, an analysis was conducted using the time-average drying rates from each surrogate drum. In this calculation, the drums were assumed to be initially empty and loaded at a constant rate of 1 and 5 kg/day for 40 and 208 L drums, respectively. Assuming a fixed drying rate equal to the observed average drying rate for the entire testing period, the average time to fill each drum toilet was calculated.

RESULTS AND DISCUSSION

Year 1 field test: 208 L drums

Figure 2(a) shows the mass of FS in the 208 L surrogate drums measured over a period of 272 days. The drums contained fecal matter, urine and wash water from each household. The average solids content of the FS at the start of the drying period was 4% for both surrogate drums. The mass of the drums decreased linearly from 198 to 130 kg in 43 days for Drum 1 (Verma Sail) and 214 to 125 kg in 54 days for Drum 2 (Vijay Nagar). The slopes of mass reduction for each drum are similar for the first 100 days, indicating that the moisture flux through the laminates was comparable during that time period. At the 100th day, Drums 1 and 2 weighed about 89 and 87 kg, respectively, with a solids content of about 10% (calculated using mass balance). However, the drying rate for Drum 2 became greater than Drum 1 after the 100th day until the next sludge refill at the 220th day. The spikes in sludge weight are due to the refilling of the drums with the collected sludge from the respective active drums. The weighing scale and the surrogate drums were initially placed in close proximity to the active toilets for comparative purposes. However, due to space restrictions and malodor from the fecal matter, the full surrogate drums were transported from their respective households to a covered open area adjacent to a community toilet, where they were stored from the 111th day until the end of the field study. Over the period of the field tests, liquid levels ranged from 79 to 12 cm and 80 to 3 cm for Drums 1 and 2, respectively.

The observed moisture fluxes obtained for each surrogate drum are presented in Figure 2(b) and 2(c). Measurement errors were noticeably larger for some data collected during the first 75 days, which is due to uncertainty in the recorded times of mass readings by field workers. Predicted moisture fluxes are also shown from the stagnant film model using the average *RH* and temperature over the time period of measured drying data (see Supplementary data). Over the entire testing period, FS in 208 L laminate-lined drums dried at a time-weighted average drying rate of 0.8 and 0.9 kg/day for Drums 1 and 2, respectively. The observed and predicted drying rates were largest in the hotter and drier months of April, May and June (Days 0–90) with average temperatures of 32 ± 4 SD °C (SD = one standard deviation) and an average *RH* of 59 ± 12 SD% (see Supplementary Material, Figure S4). On the other hand, the colder months (average temperature = 23 ± 5 SD °C and $RH = 70 \pm 8$ SD%) of October, November and December (Days 185–272) exhibited the lowest moisture fluxes. Over the entire drying period, the average model-predicted drying rates were 1.6 and 1.4 kg/day for Drums 1and 2, respectively.

For both drums, wind speed averaged over each measurement period was compared with residual (observed – predicted) drying rate (Supplementary Material, Figure S5). For the first 111 days, despite the scatter in data the Pearson's correlation coefficient between residual and wind speed was $r = 41$ and $r = 34\%$ for Drums 1 and 2, respectively, which indicates a moderate linear correlation between wind speed and model error for this period (WHO (World Health Organization) & UNICEF 2017). The model usually underpredicted the drying rate when the wind speed was high. After the surrogate drums were moved to the common community location on Day 111, the model error was smaller but the correlation between residual and wind speed for both is Drum 1 ($r = 45\%$) and Drum 2 ($r = 62\%$). Hence, the stagnant film model, which neglects wind, was less efficient in predicting drying rates for both Drum 1 (normalized root-mean-square error (NRMSE) = 61%) and Drum 2 (NRMSE = 56%). This suggests the need for a better mass transfer model than the

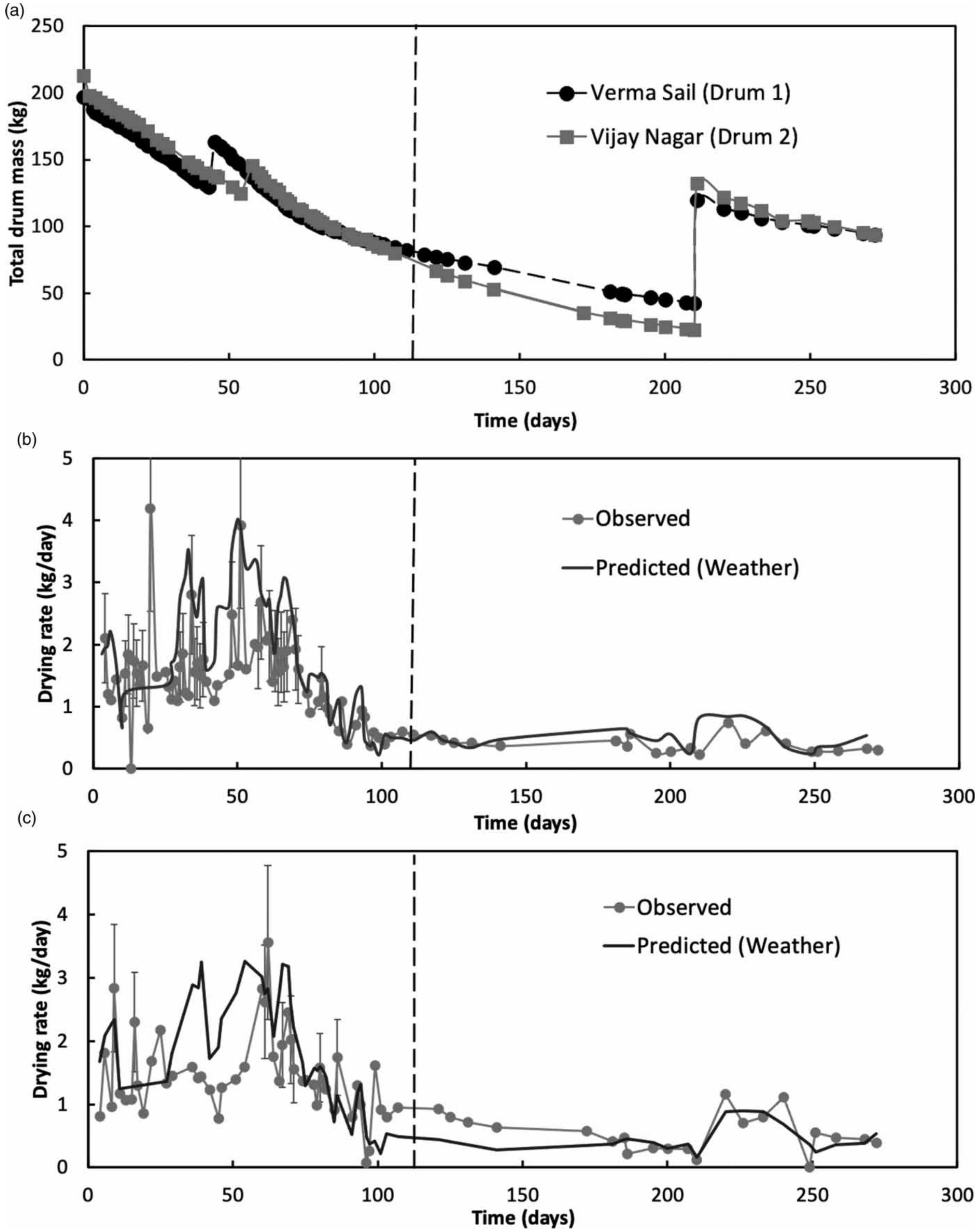


Figure 2 | (a) Decrease in total drum mass over time in 208 L surrogate drums in Year 1. The drums contained fecal matter, urine and wash water from each household. FS was added to Drum 1 on Days 47 and 220, and Drum 2 on Days 60 and 220, as indicated by the sharp rise in total drum mass. Observed and predicted drying rates (kg/day) for (b) Verma Sail (Drum 1) toilet and (c) Vijay Nagar (Drum 2) in Year 1. The error bars represent the estimated 95% confidence intervals of measurement error. Errors less than ±0.5 kg/day are not shown to improve readability. The surrogate drums were moved from their individual households to a common community location on Day 111.

simple stagnant film model to account for the effect of wind speed and perhaps wind direction on the moisture flux.

Table 1 assesses the influence of the laminate on the frequency of toilet emptying at Verma Sail (Drum 1) and Vijay Nagar (Drum 2). Assuming a constant input of 5 kg/day for each household, *in situ* drying of FS in laminate-lined drums reduced the average filling rate to 4.2 kg/day for Drum 1 and 4.1 kg/day for Drum 2. The laminate extended the filling time for each drum by an average of 8 days or 19% when compared with a regular container system.

Table 1 | Analysis of field data from breathable laminate-lined 40 and 208 L drums

	Verma Sail (Drum 1)	Vijay Nagar (Drum 2)	Govind Nagar (Drum 3)	Vijay Nagar Maline (Drum 4)
Field test				
Average loading rate (kg/day)	5.0	5.0	1.0	1.0
Average drying rate (kg/day)	0.8	0.9	0.32	0.30
Total drum volume (L)	208	208	40	40
Days to fill (calculated with laminate)	49	51	59	57
Days to fill (calculated without laminate)	42	42	40	40
Stagnant film model with meteorological data				
Predicted drying rate (kg/day	1.6	1.4	0.39	0.41
Percentage error between field observed and predicted drying rate	− 52	− 33	−18.2	−28
When the drum is full of fresh FS, it can be left to dry before transportation and treatment. The time needed to dry a full laminate-lined drum will be				
Solids content of fresh FS (%)	4.0	4.0	16	17
Water content of initial drum (kg)	200	200	34	33
Days to empty without additional loading (calculated)	259	219	106	112

Year 2 field test: 40 L drums

The laminate-lined 208 L drum system presented a number of management problems. The large volume of collected FS (208 L) made it hard to handle and dispose of when the drum was full. Hence, the shift to a smaller, more compact 40 L drum made transportation and disposal easier. Furthermore, the smaller dimensions of the 40 L drum allowed the drums to be lined with a single piece of laminate fabric, eliminating the sewing of the membrane laminate, which reduced the overall construction cost of the laminate-drum system and avoided potential leaking due to wear and tear at the seams. The separation of human excreta accounted for an increase in the average solids content of freshly collected FS from 4% in the 208 L drums to 16% in the 40 L drums.

To evaluate drying from laminate-lined 40 L drums, two surrogate drums were filled with approximately 35 kg of fecal matter from their respective EVTs and weighed periodically for 283 days. These surrogate drums were kept at a common location adjacent to a community toilet for the entire drying period. Mass losses from these surrogate drums, Drum 3 (Govind Nagar) and Drum 4 (Vijay Nagar Maline), are presented in Figure 3(a). Drying trends in Drums 3 and 4 were similar, suggesting that the cumulative, aged FS solids content was comparable in the two surrogate drums after this date. Total moisture losses from 40 L drums in Year 2 were 88.3 kg (Drum 3) and 82.3 kg (Drum 4) in a period of 283 days.

To apply the stagnant film model, $\lambda = 1.55 \times 10^{-2}$ m was used for FS drying in the laminate-lined 40 L drums, using weather data reported by the Air Quality Monitoring Station at Nehru Nagar, Kanpur, Uttar Pradesh (Tilmans *et al.* 2015). The observed and predicted mass fluxes for 40 L EVT surrogate drums are presented in Figure 3(b) and 3(c). Over the entire drying period, the average observed drying rates were generally low for both drums, except from Day 200 to Day 240. An average drying rate of 0.31 kg/day was observed for both drums from Day 0 to Day 200, which rose to 0.52 and 0.49 kg/day for Day 200 till the end of the test for Drums 3 and 4, respectively. The stagnant film model drastically overpredicts the drying rate in the first 100 days and underpredicts it in the last 100 days for both drums. Over the entire drying period, the error associated with the stagnant film model for Drum 3 (NRMSE = 109%)

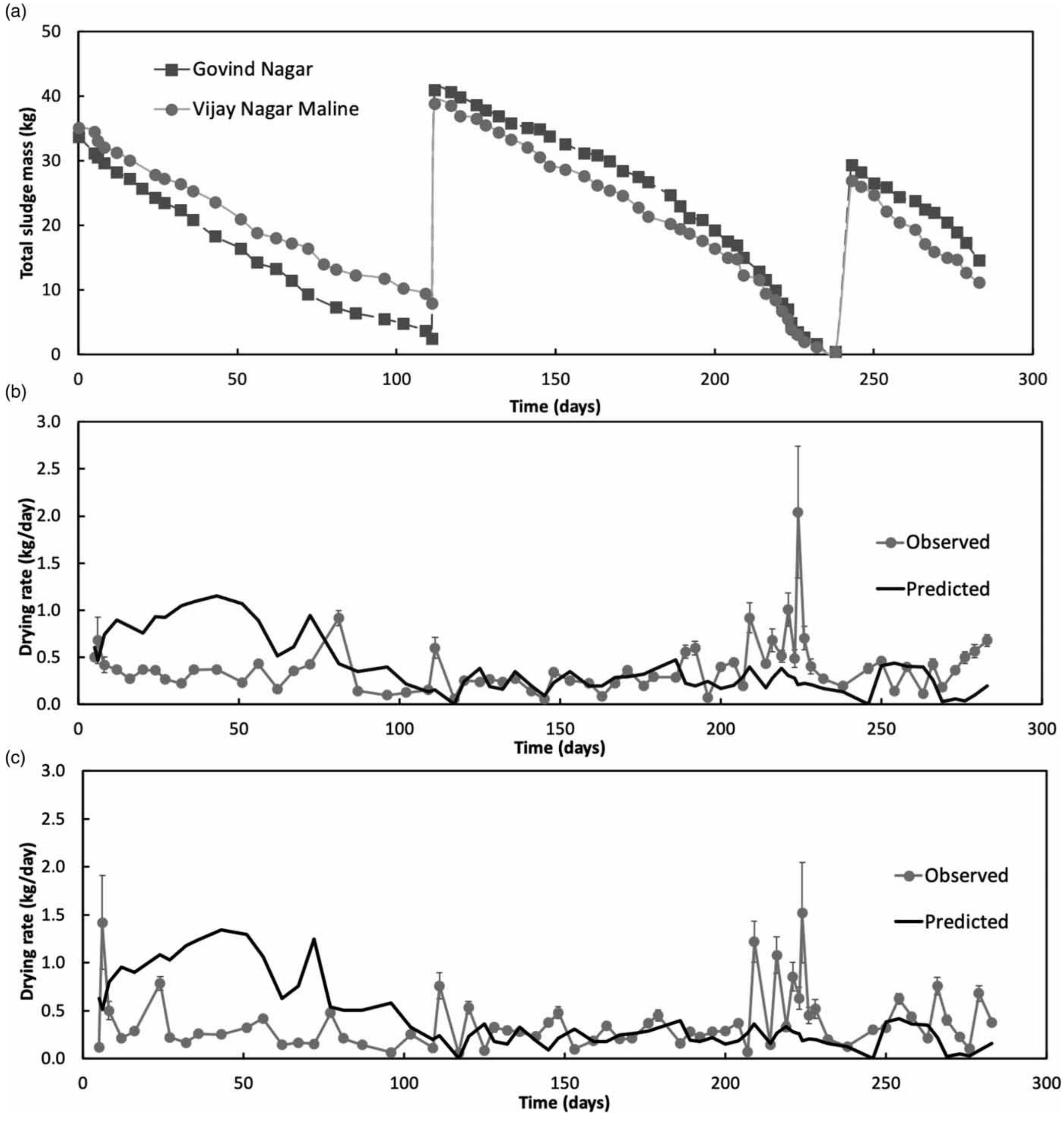


Figure 3 | (a) Decrease in FS mass over time in 40 L surrogate drums in Year 2. The drums only contained fecal matter from each household (no urine and wash water). Fecal matter was added to both surrogate drums on Days 112 and 243, as indicated by the sharp rise in the total sludge mass. Observed and predicted drying rates (kg/day) over the 283 day drying period for (b) Govind Nagar (Drum 3) and (c) Vijay Nagar Maline toilet (Drum 4) in Year 2. The error bars represent the estimated 95% confidence intervals of measurement error. Errors less than ±0.5 kg/day are not shown to improve readability.

and Drum 4 (NRMSE = 128%) were much larger than the error observed in 208 L drum drying tests. In contrast with the 208 L drum tests, the residual (observed – predicted) drying rates were negatively correlated with time-averaged wind speed data ($r = -45\%$ for Drum 3 and $r = -42\%$ for Drum 4; Supplementary Material, Figure S6). The model overpredicted drying during the first 100 days when the wind speeds were high (0.9 ± 0.6 SD m/s). During the month of October (Days 207–232) when wind speeds were smallest (0.3 ± 0.1 SD m/s), though, mass fluxes were highest and the model underpredicted drying. Based on the computational fluid dynamics modeling of EVTs, the stagnant film model, which neglects wind, was expected to underpredict drying when wind speeds are high and overpredict drying when wind speeds are low (Zhang *et al.* 2012), which was opposite to what occurred here. The reasons for the low observed drying rates in the first 100 days and high drying rates in the last 100 days for both 40 L drums are unknown but may be due to environmental anomalies not recorded by the meteorological sensors, such as an increase/decrease in localized wind speed or the presence/absence of a localized heat source that altered the temperature in the vicinity of the laminate.

The average drying rates per WSA were 1.58 and 1.50 kg/day/m^2 for Drums 3 and 4, respectively, over the 283 day period. These moisture fluxes are approximately two times larger than the average flux rates observed for the 208 L EVTs – 0.76 kg/day/m^2 for Drum 1 and 0.70 kg/day/m^2 for Drum 2, under similar climatic conditions. The difference in surface area normalized drying rates is likely due to the larger WSA to volume ratio of the 40 versus 208 L EVT design: for half-full and full drums, the surface area to volume ratio is 1.7 times larger for the 40 versus 208 L EVT design. While the 208 L drum is larger and holds more FS mass, the 40 L drum is more efficient in drying FS per unit laminate surface area.

A time-weighted average drying rate of 0.3 kg/day was calculated for each 40 L drum over the entire 283 day drying period, while the model-predicted average drying rate was 0.39 kg/day for Drum 3 and 0.41 kg/day for Drum 4. Despite the large NRMSEs determined for individual drying rate measurements reported above, the overall model-predicted drying rate was small. The most significant model error occurred in the first 100 days, when the model overpredicted drying for both drums. The percentage error between observed and predicted drying rates were much smaller for Drum 3 (−18.2%) and Drum 4 (−28%) in Year 2 than for Drum 1 (−52%) and Drum 2 (−33%) in Year 1. In both 208 and 40 L drums, the stagnant film model predicts a higher moisture flux using the meteorological data.

Table 1 summarizes the analysis of the performance of a laminate-lined 40 L drum EVT. An empty container is assumed to be filled with FS at a constant loading rate of 1 kg/day, which was estimated based on four uses per day. Assuming the laminate-lined 40 L drum has a fixed drying rate of 0.3 kg/day, the EVT would take an average of 18 more days to fill than a non-laminated 40 L drum, an increase of approximately 45%.

The aim of the laminate-lined toilets is to reduce the filling rate to decrease the disposal frequency of FS. The time saved on each disposal cycle also amounts to savings in yearly maintenance cost for the toilet users. Other design improvements, such as adding a heat source, better ventilation and increasing membrane surface area, may be considered to increase the FS drying rates further.

CONCLUSIONS

The application of breathable laminates in 208 L (55 gallon) drum EVT systems resulted in a mass transfer rate of 0.8 and 0.9 kg/day in Kanpur, India. The stagnant film model using ambient temperature and relative humidity conditions from meteorological data predicted this moisture flux within a 40% error. These containers successfully dried fecal waste at the point of collection, which helped delay the disposal frequency by at least 8 days, a 19% increase in replacement time, for a toilet being used four times a day with 1 L of wash water per use.

Modified EVTs using a smaller drum and waste segregating toilet pan were tested in two new households in urban slums of Kanpur. The average moisture fluxes observed for these 40 L drums were approximately twice as high as the 208 L drum EVTs due to the increased WSA to volume ratio of the laminate. These drums saved an average of 18 days in disposal frequency due to waste segregation (i.e., lower loading rates) and higher mass flux rate, which is a 45% increase in replacement time. Further work is needed to improve the stagnant film model to accurately incorporate effects of natural ventilation, heat transfer and solids content on moisture flux across the laminate.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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