Research Paper

In-situ drying of faecal sludge in breathable membrane-lined collection containers

Shray Saxena, Babak Ebrazibakhshayesh, Steven K. Dentel, Paul T. Imhoff and Daniel K. Cha

ABSTRACT

Drying of faecal sludge enclosed in a breathable, hydrophobic membrane laminate was investigated for the potential application of breathable membranes in decentralized container-based sanitation systems for developing nations. Moisture loss from the membrane-enclosed faecal sludge was studied using membrane 'envelopes' filled with faecal sludge collected from random volunteers. A drying test with a new membrane envelope resulted in 71.2% mass reduction over a period of 7 days with an average moisture flux of 0.73 g/day-cm^2. Slight decrease in the sludge drying rates was observed over five reuses of the same membrane envelope. A stagnant film model was used to predict drying rates of membrane-enclosed faecal sludge in ten developing countries with high urban populations. Based on a loading rate of 15 L/day into a 200-L (55-gallon) collection container, the predicted drying rates range from 7.1 to 12.4 L/day. The filling time of the membrane-lined container decreased due to in-situ drying, resulting in longer operation time and less frequent emptying of the container.

Key words | breathable membrane, container-based sanitation, faecal sludge drying, modelling, moisture transport

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INTRODUCTION

In 2015, 2.3 billion people in the world (about 32% of the total global population) do not have access to even basic sanitation services (WHO & UNICEF 2017). Around 892 million of these people practice open defecation often with no privacy while the rest are limited to shared toilets and open pit systems. The goal of this research is to address the sanitation problem of open defecation with a reliable and sustainable toilet system using breathable laminate-lined containers. The WHO and UNICEF describe basic sanitation as facilities that ensure hygienic separation of human excreta from human contact and are specifically not shared with other households (Mara & Evans 2017). This definition serves as the guideline for this research.

Sanitation systems include conventional sewerage and on-site systems, such as septic tanks, leach pits and pit latrines. These on-site systems were traditionally viewed as temporary solutions until sewers could be built; however, they now serve 2.7 billion people worldwide as sewers have not kept pace with the rapid urban expansion of low- and middle-income countries (Strande *et al.* 2014). Though these on-site facilities provide a safe and private place for defecation, they have had limited success in many poor urban neighbourhoods where the narrow, irregular street layouts prevent emptying of faecal sludge using suction trucks (Russel *et al.* 2015). Additionally, there is increasing evidence that lack of adequate regulation of on-site systems,

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like septic tanks and pit latrines, compromise water quality due to groundwater contamination (Withers 2014; Shivendra & Ramaraju 2015; Quamar et al. 2017; Chuah & Ziegler 2018; Marques Arsénio et al. 2018).

In such areas, container-based sanitation (CBS) has recently received increasing attention as a potential alternative to traditional on-site systems (Mara & Evans 2017; Orner & Mihelcic 2018). A CBS toilet system collects waste in sealable containers that are transported and disposed of once full (Tilmans et al. 2015). CBS toilet systems have been reported as early as 1894 in Victorian England where it was known as the Rochdale Pail system (Hardy 2015). Since then, basic CBS systems have been applied in remote and impoverished areas of Haiti, Ghana, Kenya and Canada (Van Der Geest 2002; Daley et al. 2014; London & Esper 2014; Tilmans et al. 2015). CBS presents several potential advantages over on-site systems, which include containment of faecal sludge with easy disposal and an overall simpler management strategy for faeces (Russel et al. 2015).

Breathable membranes are typically made from polytetrafluoroethylene (PTFE), polypropylene (PP) or polyvinylidene fluoride (PVDF), and commercially available membranes are laminated with fabrics on both sides to protect the membrane from wear and tear (Alkhudhiri et al. 2012). For hydrophobic breathable laminates, water and any dissolved ions are retained, while water vapour passes through. Hence, these membranes are commercially used to concentrate aqueous solutions in a process known as membrane evaporation (ME) (Hengl et al. 2007). This process, similar to membrane distillation (MD) processes, is driven by vapour pressure gradients, typically caused by a difference in temperature (Gryta 2011). For example, in direct contact MD, the feed is a warm process liquid and the stripping gas (or liquid) is a cold distillate, with the fluids separated by the membrane. The gradient in vapour pressure created by the temperature difference allows the permeate to diffuse from the feed to the distillate, thereby concentrating the feed.

The MD process has been shown to work effectively using low-grade waste heat at atmospheric pressure conditions, making it more energy efficient than evaporation/distillation techniques or pressurized membrane technologies like reverse osmosis (Chung et al. 2014). Gibson & Schreuder-Gibson (2009) reported a water vapour flux in the range of 6,000–6,500 g/day-m^2 for an untreated expanded PTFE membrane using 30 °C, 2,000 cm^3/min gas flow rate and a 50% humidity gradient.

Marzooghi et al. (2017) recently reported an application of breathable laminate for drying of anaerobically digested biosolids. Under moderate temperature gradients ($T = -2$, 2 and 10 °C), the moisture content of biosolids decreased from 97% to 12–30%. As a follow-up study to Marzooghi's work, the research presented here examined drying of faecal sludge enclosed in membrane laminates, evaluated possible loss of performance after multiple reuse of laminate and tested a different laminate that has more favourable vapour transport properties than the laminated membrane used by Marzooghi. The proposed laminate-lined toilet system will allow drying of faecal sludge during collection and improve the storage duration of the container, thus reducing the frequency of container replacement and sludge disposal.

MATERIALS AND METHODS

The three-layered eVent laminate used for this study was purchased from CLARCOR Industrial Air (Overland Park, KS, USA). This laminate contains a 46.4-μm thick gas permeable ePTFE membrane that is hydrophobic. The pore size of the membrane was determined by the Brunauer–Emmett–Teller (BET) method using a Micromeritics ASAP 2020 analyser. Membrane thickness was observed under a Hitachi S-4,700 scanning electron microscope (see Table 1 in the Supplementary data, available with the online version of this paper). It is supported by a hydrophobic 300D polyester fabric (0.15 mm) on one side and a hydrophilic 20D mesh-like tricot layer backing fabric on the other side.

The faecal sludge used for this experiment was collected from student volunteers at the University of Delaware participating in a collection drive. A 19 L (5-gallon) capacity portable toilet with flush capability was used to collect faecal matter. The volunteer drive was anonymous and held inside a private toilet for 96 hours. The collected faecal sludge included flush-water and urine, but no toilet paper. The sludge was stored in a refrigerator at 4 ± 1 °C till used in the drying experiments.

Table 1 | Drying predictions based on stagnant film model for proposed toilet system in ten developing countries of the world

Field test predictions	Average loading rate (litres/day)	Average drying rate (litres/day)	Average filling rate (litres /day)	Total drum volume (litres)	Days to fill (without membrane)	Days to fill (with membrane)	Days saved per disposal cycle
Brazil	15	11.51	3.49	200	13	57	44
Pakistan	15	11.86	3.14	200	13	64	50
Nepal	15	8.34	6.66	200	13	30	17
Laos	15	12.36	2.64	200	13	76	63
India	15	11.76	3.24	200	13	62	48
Bangladesh	15	12.20	2.80	200	13	71	58
South Africa	15	7.13	7.87	200	13	25	12
Kenya	15	8.84	6.16	200	13	32	19
Ethiopia	15	8.07	6.93	200	13	29	16
Egypt	15	11.47	3.53	200	13	57	43

Average drying rate is calculated based on ten-year average temperature data (2006–2016) and for 50% ambient RH.

Laminate envelope drying test

Laminate envelopes used for faecal sludge drying tests were fabricated by cutting out one side of a polyethylene (PE) plastic collapsible bottle and replacing the removed section with a laminated membrane sheet. The laminate was attached to the bottle using silicone glue with the mesh-like tricot layer side of the fabric facing the inside of the bottle. Each envelope had airtight caps for addition and removal of faecal sludge. The collapsible bottles were 13.9 cm wide × 25.4 cm high with a total volume of 0.6 L. A laminate surface area of 120 cm^2 was used to dry each envelope. The envelope drying experiments were conducted with the laminate-side of the envelope facing upwards.

For each experiment, triplicate laminate envelopes were filled with 100 mL faecal sludge and placed on a Mettler Toledo XP4002S Balance (Columbus, OH, USA) to monitor mass loss within ±0.01 g accuracy. All drying experiments were conducted in a climate room set at 30 °C. The humidity of the climate control room was maintained at 25% using a dehumidifier. The ambient temperature and humidity were monitored using Micro-DAQ EL-USB-2 RH/temp data loggers (Contoocook, NH, USA). Total solid concentration of faecal sludge was determined after drying according to Standard Methods 2540 B (APHA *et al.* 1960). Mass loss from an envelope containing 100 mL of deionized (DI) water was monitored in parallel as a control.

After seven days of drying, the laminate envelopes were emptied of any residual faecal solids, rinsed with DI water and oven dried at 105 °C for 1 h. The envelopes were re-filled with 100 mL of faecal sludge or DI water for the next drying cycle. These steps were repeated for five drying cycles. Due to an instrument error, climate room ambient temperature and humidity data was not recorded for the last two cycles.

RESULTS AND DISCUSSION

Mass losses from laminate envelopes filled with faecal sludge and DI water (as control) are presented in Figure 1. The mass of sludge in the laminate envelopes decreased rapidly and linearly from 96 g to 33 g in 24 hours. Following the initial rapid drying period, moisture loss from the faecal sludge was more gradual, resulting in 0.8 g after 7 days. The total solids content of the laminate-enclosed faecal sludge increased from 2.4% to 65.8% in 24 hours and finally to 99.2% in 7 days. The completely dried faecal sludge sample exhibited a wafer-like consistency throughout, indicating that thorough drying occurred consistently across the breathable laminate.

Faecal matter is made up of water, protein, undigested fats, polysaccharides, bacterial biomass, ash and undigested food residues (Russel *et al.* 2015). In addition, faecal matter contains water at 50–90% moisture content (Nishimuta

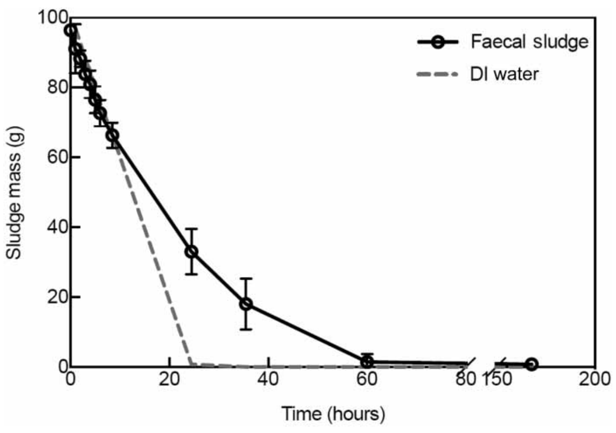

Figure 1 | Drying of faecal sludge in new eVent laminate envelopes. Data points and error bars represent the average of triplicate envelopes and standard deviation, respectively.

et al. 2006). Moisture can be present in and around the solid particles as: (1) free water; (2) interstitial water, which is trapped between particles due to capillary action; (3) surface water, enveloping the particles due to adhesion and adsorption; and (4) bound water, which is enclosed between or chemically bound to particle aggregates (Chen et al. 2002). During sludge drying, removal of water progresses in the order of free water, interstitial water, surface water and finally bound water. Hence, sludge drying curves typically exhibit a constant rate period for free water evaporation, followed by decreasing drying rate periods due to interstitial, surface and bound water removal (Chen et al. 2002).

Average mass loss from the reused envelopes monitored over five drying-and-reuse cycles is presented in Figure 2. Moisture flux across the laminate was calculated for the

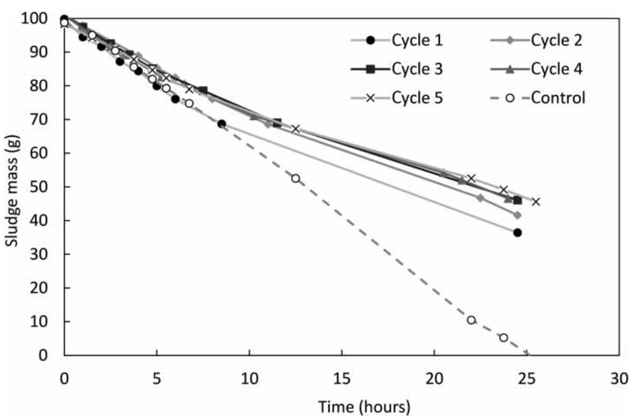

Figure 2 | Sludge drying curve over five drying-and-reuse cycles. The first cycle control data is compared to five different faecal sludge cycles.

linear region of each drying curve by dividing the initial 12-h drying rate by the total laminate surface area ($120\ cm^2$). For the first drying cycle with unused laminate envelopes, an average faecal sludge drying rate of 0.73 ± 0.02 g/day-cm^2 was observed while the control envelope dried at 0.84 ± 0.02 g/day-cm^2. Thus, drying rate of faecal sludge was lower by approximately 13% over DI water. In similar drying experiments conducted with anaerobically digested biosolids in a GORE Wrap Cover laminate, drying rates of biosolids were slower by approximately 31% over DI water during the linear drying region (Marzooghi et al. 2017). Thus, the effect of solids in the eVent laminate with faecal sludge is significantly less than GORE Wrap Cover laminate with anaerobically digested biosolids.

The moisture flux during the second sludge drying cycle decreased to 0.59 ± 0.04 g/day-cm^2, but the flux remained relatively unchanged during the subsequent drying runs. Even after the fifth drying cycle, less than 10% decrease in faecal sludge drying rate (0.54 ± 0.03 g/day-cm^2) was observed compared to the first cycle. Although the slight decrease in sludge drying rate observed between the first cycle and all other cycles suggests minor clogging of the laminate, this is likely a function of the cleaning procedure, which only involved mild rinsing. Additional work is needed to examine build-up of deposits on the laminate and the utility of more vigorous cleaning (e.g. mild brushing in addition to rinsing with water), which may be readily employed in the field.

Modelling of drying through membrane laminate

Faecal sludge drying is limited by moisture transfer through the membrane laminate. Marzooghi et al. (2017) presented a mathematical model for moisture transfer through a laminated membrane, where transport was described separately through the membrane and two protective fabrics. Although Knudsen diffusion is an important process controlling transport through many hydrophobic membranes (Zhang 2006), it played a minor role in a GORE Wrap Cover laminate given the slow rate of molecular diffusion through the thicker protective fabrics (Marzooghi et al. 2017). Instead, mass transfer was adequately described with only molecular diffusion through a single composite layer that accounted for resistance through the membrane and fabrics (Marzooghi et al. 2017).

A similar analysis was applied to the three-layer eVent laminate used in this study using measured and estimated membrane properties (see the Supplementary data, available with the online version of this paper). If Knudsen diffusion is neglected and mass transfer is described by molecular diffusion alone, the error in mass transfer resistance is less than 2%. Thus, in the analysis below molecular diffusion was assumed to describe moisture transport through the laminated membrane that was treated as a single composite layer.

Water vapour flux across the three-layered laminate was described for the constant rate drying period using a stagnant film model (Sherwood et al. 1975; Marzooghi et al. 2017):

$$N_A = \frac{P}{R(T_{avg}+273.15)}\frac{D_{AB}(T_{avg})}{\lambda}\ln\left(\frac{P-p_{A_1}}{P-p_{A_2}}\right) \quad (1)$$

where N_A is the molar flux of water across the laminate per unit area (mol.m^{-2}.sec^{-1}), P is the average total gas pressure across the laminate in Pa, R is the ideal gas constant (J.mol^{-1}. K^{-1}), T_{avg} is the average temperature across the laminate in °C, p_{A1} is the water vapour pressure on the faecal sludge side and p_{A2} is the vapour pressure on the air side in Pa. The effective diffusion length, λ (m), is defined as:

$$\lambda = \delta\tau/\varepsilon \quad (2)$$

where δ is the laminate thickness in m, τ is the dimensionless tortuosity and ε is the porosity. $D_{AB}(T_{avg})$ is the diffusivity of water vapour in air (m^2. sec^{-1}) and is estimated using the Fuller equation (Gibson 2000):

$$D_{AB}(T_{avg}) = (2.23\times10^{-5})[(T_{avg}+273.15)/273.15]^{1.75} \quad (3)$$

At the sludge–laminate interface, the relative humidity is assumed to be approximately 100%. This assumption will be valid as long as free water is present in the sludge (Vaxelaire et al. 2000). Hence, the vapour pressure at the sludge–laminate interface (p_{A1}) is equal to the saturated vapour pressure of water that is estimated with the Arden Buck equation (Buck 1981):

$$p_{A1} = 6.1121\times100 \times \exp\left(\left(18.564-\frac{T}{255.57}\right)\left(\frac{T}{254.4+T}\right)\right) \quad (4)$$

where T is the sludge temperature. Since T was not measured in this work, it was assumed equal to the ambient temperature. Vapour pressure at the air–laminate interface (p_{A2}) is also calculated using the Arden Buck equation and the measured relative humidity of air (RH):

$$p_{A2} = (\text{RH}\%)\times p_{A1} \quad (5)$$

Applying the stagnant film model to the initial drying period (0–12 h) for the first three drying cycles of the laminate envelope test, best-fit λ were determined using Solver in Microsoft Excel. Temperature of the faecal sludge in the laminate envelopes was assumed to be the same as the ambient temperature of the climate-controlled room, which varied from 28.7 ± 0.1 to 28.9 ± 0.1 °C between cycles. For a new laminate envelope, the calculated λ values were $(6.1\pm0.2)\times10^{-3}$ m and $(5.48\pm0.13)\times10^{-3}$ m for faecal sludge and control, respectively. The λ values for DI water stayed relatively constant over three drying cycles, while the faecal sludge λ increased to $(7.64\pm0.14)\times10^{-3}$ m in the second drying cycle and to $(8.2\pm0.3)\times10^{-3}$ m in the third cycle.

A higher resistance to moisture flux in the faecal sludge envelopes and the increase in faecal sludge λ over each cycle suggests that the presence of solid particles in faecal sludge may alter the porosity of the laminate. Marzooghi et al. (2017) noted a similar phenomenon and suggested that biosolids blocked some laminate pores, resulting in larger λ for biosolids than DI water experiments. Marzooghi et al. (2017) reported λ value of 9.5×10^{-3} m for DI water drying across a GORE Wrap Cover laminate. This is a 44% larger effective diffusion length than the eVent laminate used in this study, which will correspond to a 44% smaller DI water drying rates under similar vapour pressure gradients. In comparison with a range of commercial membrane laminates, the eVent laminate outperformed most breathable laminates while showing little variation with mean humidity levels (Gibson & Schreuder-Gibson 2009).

Proposed application of breathable membrane in toilets

The proposed breathable laminate-lined toilet system consists of a toilet seat and collection vessel lined with an e-Vent laminate enclosure. Breathable laminate in the collection vessel acts as a physical barrier to faecal sludge, thus preventing human exposure and leakage to the environment while allowing drying of the faecal sludge by water evaporation through the laminate to the surrounding atmosphere. In addition to its environmental benefits, a breathable laminate will allow the collection container to be replaced less frequently as faecal sludge will undergo drying while in the collection container. This in-situ drying of collected sludge in the container presents an opportunity for a toilet to be sustainable for a much longer period without emptying under hot and arid conditions.

If the λ value is known for a particular breathable laminate, in-situ drying of sludge in a collection container can be estimated using the stagnant film model with the ambient temperature and relative humidity data. Based on a ten-year average temperature (2006–2016, see Table 2 in the Supplementary data, available online) and for 50% ambient relative humidity, the performance of the proposed laminate toilet in ten countries with high urban population was predicted using a λ value of 6.1×10^{-3} m obtained from the laminate envelope test. The predicted drying rates are tabulated in Table 1. These estimates for the 50% ambient relative humidity case were calculated for an eVent laminate bag fitted inside a standard size 200-L (55-gallon) drum.

The drum is assumed to be well ventilated, such that resistance to drying is dominated by water vapour transport through the laminate. The container-based toilet system is estimated to have a loading rate of 15 L/day based on six daily uses with 0.25 kg/use/capita of faecal sludge generation and 2.25 kg/use of water input in the form of urine, wash-water and flush water (Montangero & Strauss 2002). This faecal sludge is added assuming the same temperature as outside ambient conditions while the moisture content is assumed to remain sufficiently high to maintain the sludge–laminate interface at RH = 100%. The laminate surface area for drying is assumed to be the total surface area of the drum (1.85 m^2).

The analysis shows that the drying rates of laminate-enclosed faecal sludge ranged from 7.13 to 12.4 L/day (Table 1), and the presence of e-Vent laminate increases the time to fill a standard 200 L drum from 13 days without the laminate to 25–76 days with the laminate. In order to account for the variability of relative humidity, sludge drying analysis was repeated for four ambient relative humidity conditions: 40%, 50%, 75% and 90%. For example, in South Africa, the cities of Upington, Johannesburg and Durban have a mean RH of 40%, 59% and 77% respectively recorded over the period of 1961–1990 (see the Supplementary data). Figure 3 compares the predicted daily loss of sludge mass due to drying for ten countries over RH values of 40%, 50%, 75% and 90%. Figure 3 shows that loss on drying, calculated as a ratio of the predicted drying rate to the loading rate of 15 L/day, is higher for countries with hot and dry climates. For example, countries such as Egypt, Bangladesh, India, Laos, Pakistan and Brazil provide a greater opportunity for container-based toilets to be sustainable. For those countries with warmer climates, even a 50% RH condition results in more than 11 L/day of moisture loss. Hence, the users will be able operate the toilet in these countries by interchanging two collection vessels. Once the collected sludge is dried to the desired moisture content, the remaining solids may be composted or transported to a nearby wastewater treatment plant.

The predicted sludge drying data presented in Table 1 and Figure 3 provide a best-case scenario for the laminate-lined container under a well-ventilated condition and do not consider practical design and operational limitations. For example, an air gap must be maintained between the breathable laminate layer and the drum outer wall to ensure mixing with fresh air flowing into the system, and the laminate must be properly cleaned to minimize the

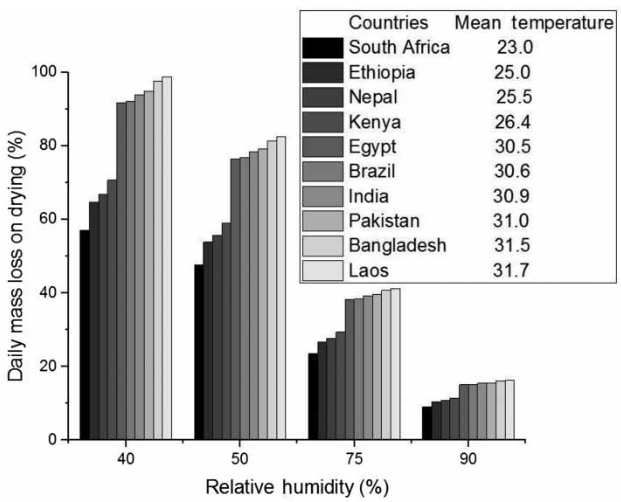

Figure 3 | Daily mass loss on drying for the proposed breathable membrane toilet system predicted for ten developing countries over four ambient relative humidity conditions. Temperature in the legend is ten-year average temperature for each country.

clogging of laminate pores. In addition, the above analysis does not consider factors that may affect faecal sludge drying: (1) heat generated from microbial activity, which enhances drying; (2) variable water vapour transport across the laminate surface due to varying wetted surface area; and (3) decrease in sludge moisture content at the laminate–atmosphere interface after the initial drying period, which reduces the vapour pressure at this interface below saturated conditions. For these reasons, pilot-scale tests are needed to confirm the predictions reported in Table 1. In addition, the permeability of the laminate to all gas vapours may result in emissions of odorous compounds, which may be problematic in poorly ventilated toilets. Future work is needed to develop well-ventilated membrane enclosure systems to dissipate any odours emitted at the sludge–laminate interface and to reduce stagnant air layer around the outer surface of the laminate.

CONCLUSION

Moisture loss from a breathable laminate-enclosed faecal sludge was studied using laminate envelopes. Drying tests with new laminate envelopes resulted in 71.2% mass reduction over a period of 7 days with a linear average moisture flux of 0.73 ± 0.02 g/day-cm^2. Slight decrease in the sludge drying rates was observed over five reuses of the same laminate envelope. Using the λ values obtained from the laminate envelope drying tests and the average climate data, drying rates of enclosed faecal sludge were estimated with stagnant film model for ten populated countries around the world. Based on a loading rate of 15 L/day into a laminate-lined 200 L collection container, the predicted drying rates ranged from 7.13 to 12.4 L/day. Due to this in-situ drying, the filling time of a laminate-lined container would be longer than that of a conventional container system with no laminate, resulting in longer operation time and less frequent emptying of the container.

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