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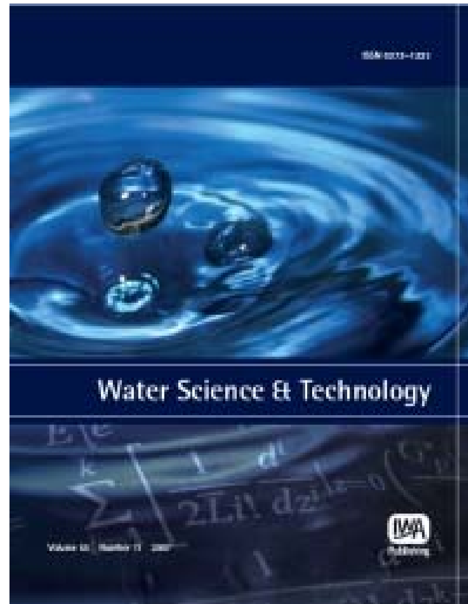

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Peepoo bag: self-sanitising single use biodegradable toilet

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ABSTRACT

Unsafe water, sanitation and hygiene together with deficient nutritional status are major contributors to the global burden of disease. Safe collection, disposal and reuse of human excreta would enable the risk of transmission of diseases to be decreased and household food security to be increased in many regions. However, the majority of the 2.5 billion people lacking improved sanitation comprise poor people in societies with weak infrastructure. This study developed a low cost sanitation option requiring little investment and maintenance—a single use, self-sanitising, biodegradable toilet (Peepoo bag) and tested it for smell, degradability and hygiene aspects. It was found that no smell was detectable from a 25 μm thick bag filled with faeces during 24 h in a 10 m^2 room at 30°C. Bags that had been in contact with urea-treated faeces or urine for 2 months in air, compost or water at 24 or 37°C showed little signs of degradation. Furthermore, pathogen inactivation modelling of the 4 g of urea present in the bag indicated that appropriate sanitation of faecal material collected is achieved in the bag within 2–4 weeks, after which the bag can be degraded and reused as fertiliser.

Key words | biodegradable plastics, disease prevention, human excreta, nutrient reuse, sanitation, single-use toilet

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INTRODUCTION

Today, 1.2 billion people do not have any sanitation system at all and need to practise open defecation, while over 2.5 billion are still without access to adequate sanitation (Unicef 2008). The sanitation solutions for the remainder of the world's population are in many cases still a source of pollution. This is because most of the sanitation systems used do not include any means of treatment of the excreta collected, which in many cases is disposed of as a pollutant into nearby water recipients. The main function of many toilets, especially in low and middle income countries, is to give the user privacy while the excreta are deposited in the toilet or just a short pipe transport away, which results in polluted water sources and restricted possibilities to reuse excreted nutrients. Unsafe water, sanitation and hygiene together with deficient nutritional status are major contributors to the global burden of disease (GBD) and contributed e.g. 19% of the 2001 GBD measured in Disability Adjusted Life Years (DALY) (Lopez *et al.* 2006). By safe collection, treatment and reuse of human excreta it would be possible to decrease the risk of transmission of diseases and increase the nutritional status in many regions. In rural areas some of the nutrients from the excreta, collected in pits or septic tanks, are commonly reused, mainly after co-treatment with animal manure. However, only approximately 300 million people are covered by an *end-of-pipe* secondary-level treatment system (Matsui 2002) and most of the wastewater collected is neither treated nor reused, or is reused in an uncontrolled manner. Untreated wastewater pollutes surface waters and groundwater and in regions affected by flooding the pollutants from the excreta can re-enter houses with rising water levels.

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Sanitation systems can be ranked stepwise according to status and functional improvement, starting with the lowest level of open defecation, via dug pits, ventilated improved pit latrines (VIP) and ending with flushed porcelain toilets at the top of the sanitation ladder (COSI 2008). In all steps the sanitation solution can be replaced by an ecological sanitation alternative providing options for reuse.

A similar ranking of sanitation systems can be made as regards the pollution from excreta (a sanitation pollution ladder). Open defecation and sanitation systems that do not treat the excreta at all prior to them entering the environment result in the worst pollution and represent the bottom rung of the ladder. One step up is an enclosed collection and simple treatment system, such as a single chamber septic tank or storage, e.g. VIP latrines not in connection with the groundwater. The next step is advanced wastewater treatment technology, where most of the nutrients are removed into the sludge, as well as simple techniques such as Arborloo (Morgan 2007) where a tree is planted in the pit. The final step is when nutrients in the excreta are not considered as a pollutant but as a resource, e.g. urine-diverting dry toilets where both the urine and faeces are re-used in a safe way.

The main objective of this project was to develop a sanitary solution that occupies the lower rungs of the sanitation ladder (just above open defecation), making it available for almost all people, but that is at the top level of the pollution ladder, producing only a safe resource.

The specific objective of the present study was to develop a single use self-sanitising biodegradable toilet including a system for collection and reuse based on filed patent SE#07005116-9. Sub-objectives were that the toilet should be easy to use, available to all, biodegradable in the environment, safe from a health perspective and produce a plant-available fertiliser.

MATERIALS AND METHODS

The Peepoo concept

The Peepoo bag is a single use toilet for collection of faeces and urine at excretion and is designed as an outer $15 \times 40\,cm^2$ bag with an inner hand cover for folding over the hand during use. The bag is opened and either held by hand or put into a small bottle, e.g. a cut 1.5 L PET bottle. The user then squats over the bag to defecate and after use the bag is sealed with a simple knot. The bag must remain odourless for over 24 h, allowing initial storage by the user (Figure 1).

The sanitising agent in the Peepoo bag is urea ($CO(NH_2)_2$), which degrades upon contact with bacterial enzymes in the faeces to form ammonia (NH_3) and carbonates, both of which contribute to pathogen inactivation (Park & Diez-Gonzalez 2003; Vinnerås *et al.* 2003; Ottoson *et al.* 2008). Since urea is stable and harmless in its undegraded state, it is the most user-friendly option for applying ammonia in a single toilet system where the user can come into contact with the disinfectant. After degradation of the bag, the contents can be used as a fertiliser since the material is enriched by the addition of urea.

Smell and function testing

A correlation between smell and bag wall thicknesses (from $<10\,\mu m$ to $25\,\mu m$) was tested using an untrained smell panel of four individuals. Faecal matter from pigs was placed in polyethylene bags, 200 g in each bag. Polyethylene was used as a general plastic material. The bag was placed in the middle of a $10\,m^2$ room with 3 m to the roof, with an indoor temperature of 30°C, and the test individuals entered the room 1 metre from the bag.

The function of the bags was tested in two sets, one in Sweden by four individuals with good sanitation conditions, who used the Peepoo bags for urination and defecation

Figure 1 | Peepoo bag with the outer bag folded down; holding the bag with hand covered by inner foil; and the used bag.

during a two-week period; and one in Kibera, Kenya, by ten individuals with poor sanitation conditions, who used the bags for urination and defecation during a one-week period.

Testing the effects of internal and external environment on plastic bags

Plastic bags, referred to as degradable bags by the supplier (size: 18 L, thickness: 25 μm), were obtained from Papyrus AB, Sweden. According to the supplier, the film material is based on polyethylene, pigments and a starch-based pro-oxidant additive. The bags were cut and heat-sealed into the form of the Peepoo bag (Figure 1).

Bags filled with faeces or urine were placed in either air, river water (from the Fyris river in Uppsala, Sweden) or compost (maturity corresponding to Rottegrad 5, i.e. still active compost) and stored for two months at room temperature (24°C) or at 37°C. The bags were then cleaned using de-ionised water and soap until no visual contaminant remained on the surface of the material.

Infrared spectroscopy (IR) analysis was conducted in order to reveal any significant physico-chemical changes or absorption/adsorption of foreign species to the material as a result of exposure to the various environments. The decision to use IR was based on the fact that it is a flexible tool and suitable for observing changes in chemical groups or species present (Coates 2000), which is a possible consequence of e.g. bag degradation. The IR spectra were obtained with a Perkin-Elmer Spectrum 2000 FTIR spectrometer (Perkin-Elmer Inc., USA) equipped with a MKII Golden Gate™, single reflection ATR system with a diamond crystal and controlled by the programme Spectrum Version 2.00 (Graseby Specac Ltd, UK). The bag surface was wiped with a tissue and then pressed onto the crystal. After each measurement the crystal and the opposing side were cleaned with acetone. At least four measurements were made on each bag sample; two on each side at the base of the bag and two approximately 2 cm from the opening. The spectra were based on 16 scans.

NH_3 migration in faecal matter

To represent different faecal composition, solid faecal material was diluted in physiological NaCl (0.85–0.90%) to give 2, 5, 10 or 15% TS (total solids) respectively. The solution was then homogenised and transferred to testing tubes, which consisted of transparent plastic tubes 5 cm in diameter and 25 cm long sealed at both ends, with 2 cm diameter sampling holes at 5 cm intervals. The tubes were placed horizontally and urea (WWR, Germany) corresponding to 2% of the total wet weight was added to one corner using a plastic tube (Ø 7 mm) to ensure precise positioning.

To detect the migration of ammonia in the material, a NH_3 electrode (Metrohm, Sweden) was placed in each of the holes in the tube to measure the ammonia concentration. The values obtained (in mV) were correlated to a standard curve. The ammonia concentration was tested after 1–5, 12 and 24 h for the 2 and 5% TS samples and on days 1, 2, 3 and 4 for the 10 and 15% TS samples.

Pathogen inactivation by urea-based sanitation

Microbial inactivation in relation to ammonia was monitored for *Salmonella* spp., *Ascaris suum* eggs and bacteriophages MS2 and ΦX in faecal material (17–20% TS) with urea added (0.5 to 2% w/w) and in urine mixed with water in proportions 1:0, 1:1 and 1:3. The complete results from this part of the project are reported by Vinnerås *et al.* (2008) and Nordin *et al.* (2009, in press). As the main source of pathogens is the faecal matter, the study only focused on the inactivation of pathogens in the faeces.

RESULTS AND DISCUSSION

Smell and function

The tests gave initial indications that when plastic material with a thickness of <10 μm was used, a strong, easily detectable smell was found in the room one hour after placement of the bag. When the thickness of the material was increased to 25 μm, no smell was detected by any of the test individuals during up to 24 h of bag exposure. It should be remembered that in addition to the thickness, factors such as the material crystallinity also affect the diffusion of odour compounds through the bag. However, such factors were not measured for any bag type, nor was the method of bag closure tested for permeability of odour.

The function testing of the single use toilet bag showed that it was easy to use and had an appreciated function in both Sweden and Kenya. All users evaluated the bag as being easy to use and most of the users appreciated the inner coating of thin plastic for hand coverage during use. The fact that the toilet is single use and offers a possibility for direct usage in the home, without causing any smell, was especially appreciated in Kibera. In addition, the information that the nutrients could easily be reused for crop production by burying the bags in the ground attracted interest from users who had small cultivation areas.

Effects of internal and external environment on the plastic material

It is important that the bag is sufficiently unaffected during the first two to four weeks in order to serve as a safe container for the sanitation of any pathogens present. The aged bags were not tested with respect to their mechanical properties, but when they were handled, they seemed to be mechanically unaffected. Varying degrees of brown/yellowish discoloration were observed in several cases, which indicated some sort of environmental or ageing-induced effect.

The most obvious variation in the IR spectra was the size of the broad peak region around 1,420 cm^{-1} for the inside of the bag, which accompanied a similar change in the size of the 873 cm^{-1} peak. This non-systematic variation also occurred for the pristine bag and was therefore suggested to be due to the material itself and not the ageing process. In regions where water was absorbed, the IR also showed variations in intensity. However, despite the surface wiping, it was difficult to determine whether these differences in intensity were due to absorption of moisture during the ageing experiments or whether they originated from the washing procedure and the subsequent non-dry storage. Nevertheless, it seemed that in several cases the water IR peaks were more intense in the lower parts of the bag compared with the upper parts. This would indicate that the bag absorbed moisture during the ageing experiments, at least in some cases, but additional measurements are needed to verify this. Apart from the above-mentioned variations, no obvious significant changes in the IR spectra were observed for the material that had been exposed to faeces, irrespective of the actual temperature and external environment. However, in the case of urine, a non-symmetrical enhanced intensity, peaking at 1,035–1,038 cm^{-1}, was observed. Although this may have contained several IR peaks, we refer to it here simply as the $\sim$1,036 cm^{-1} peak. It appeared only in the bottom part of the bag, on either one or both sides. Although more work is needed to determine the origin and cause of this peak in the present case, it may be argued that it was associated with urine species, or bag components reacting with substances in the urine. The reason is that it appeared only for urine-exposed bags, but never for the unexposed part of these bags, i.e. slightly below the opening. Since the peak was observed on both sides of the bag for several systems (i.e. 24°C, urine/air and urine/water), our conclusion was that some components of urine could diffuse into and through the bag.

Since the bag did not seem to degrade to any extent detectable with the techniques used here, these studies indicate that in environments similar to those tested (in ambient air, soil or water) the bag will remain sufficiently intact during at least two months. The slow degradation rate indicates that the material will remain a long time in the soil before degradation. However, tests with the actual bags need to be conducted in order to reveal whether the bags are sufficiently impermeable, i.e. prevent migration of pathogens, gases and liquids, to permit self-sanitation. Further studies are also needed to estimate degradation rates in different environments, e.g. to estimate the time after usage when the bags are degraded, making the contents plant-available, when the bags are no longer visible in the soil and when no traces can be detected, ensuring no accumulation of degradation products in the soil. Further studies are also needed with other plastic materials so as to ultimately identify bag materials that are totally based on renewable sources. Based on the results of this study, the material in the bags has been changed to a material based on alphatic co-polyester polylactic acid mixed with wax and lime.

NH_3 migration in faecal material and pathogen inactivation by urea-based sanitation

In studies performed on urine at different dilutions and on urea-amended faeces (Vinnerås *et al.* 2008; Nordin *et al.* 2009, in press), microbial inactivation rates have been shown to have a positive linear correlation to concentrations

of NH_3 (aq), especially at concentrations above 50 mM. However, inactivation rate increases with temperature and higher inactivation can be achieved at 34°C than 24°C at the same NH_3 (aq) concentration (Figure 2). In the single use toilet the excreta are not diluted and high pathogen concentrations must be assumed. Approximating bacterial and viral concentrations to $9 \log_{10} \mathrm{cfu\,g}^{-1}$ faeces and *Ascaris* eggs to $4 \log_{10} \mathrm{g}^{-1}$ faeces when an infected person uses the toilet bag (Westrell 2004), respective decreases in pathogen concentration of 0.64 and $0.29 \log_{10}$ per day are needed to sanitise the bag within two weeks. Extending the treatment time to four weeks would lower the pathogen inactivation rates to 0.32 and $0.14 \log_{10}$ per day, respectively.

Solving the regression functions with respect to the target inactivation rates for the respective organism gives the concentration of NH_3 (aq) that must be reached to achieve inactivation (Table 1). However, an extrapolation assuming a continuous linear relationship outside the investigated rates and concentrations was considered for some organisms (Figure 2).

Our tests showed that the target inactivation of *Salmonella* spp., which is a good model for intestinal bacterial pathogens, could be achieved at low NH_3 concentrations. For example, with concentrations just above 50 mM the target inactivation could be reached in 2 weeks for both temperatures (Figure 2). However, for *Ascaris* eggs the target inactivation at 24°C was not achieved within the range of concentration studied. Estimated concentrations of 1,300 and 610 mM NH_3 were necessary for target inactivation within 2 and 4 weeks respectively. To model viral inactivation, two bacteriophages (MS2 and ΦX) were monitored and, similarly to *Ascaris* eggs, the phage inactivation rates were low at 24°C, requiring concentrations of 840 and 890 mM NH_3 for target inactivation within 2 weeks (Table 1).

The enzymatic degradation of urea is fast and during the migration measurements an increase in ammonia was detectable within one hour of addition of urea to the material. In the material with TS corresponding to ≤5% the urea concentration was homogeneous within 12 hours in all four locations, indicating that ammonia transport within the material, with no mixing, was faster than $2.5 \mathrm{\,cm\,h}^{-1}$. When the dry matter content was increased transport became slower, taking up to three days to reach 5 cm at 15% TS. At 10% TS, transport was faster than at 15% TS but varied to some extent between different samplings.

These studies of the molecular transport of ammonia in faecal matter show that even at TS levels close to the average of 10–23% for a healthy person (Lentner *et al.* 1981), the urea becomes degraded and is distributed within the material within just a few days. As the faeces are collected separately per defecation, the ammonia transportation distance required in the material to ensure homogeneous

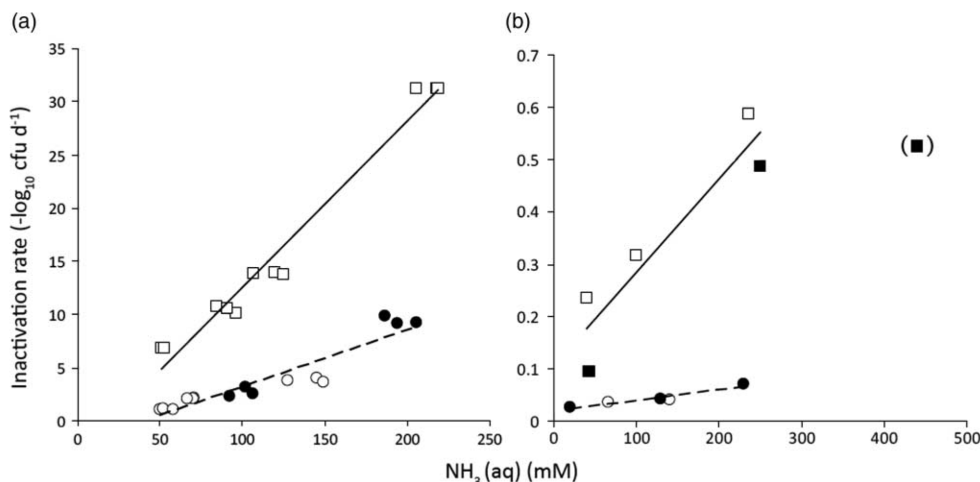

Figure 2 | Inactivation rates for (a) *Salmonella* spp. and (b) *Ascaris suum* eggs in urine (open symbols) and in faecal material (black symbols) plotted against concentration of unionised ammonia, NH_3 (aq). Lines for linear regression at 24°C (○/●) and at 34°C (□/■) are depicted with broken and solid lines, respectively. Data points within brackets (■) in (b) were excluded from the regression since the reduction rate was >0.53 but undetectable due to low sampling interval (Vinnerås *et al.* 2008; Nordin *et al.* 2009, in press).

Table 1 | Models for concentration-dependent inactivation rate, $(-\log_{10} d^{-1}) = f * [NH_3] - c$, for *Salmonella* spp., *Ascaris suum* and bacteriophages MS2 and ΦX, together with target concentrations of NH_3 (mM) that according to the model reach target inactivation rates, i.e. 4 and 9 $\log_{10}$ reduction within 14 and 28 days

Temp (°C)	Organism	Inactivation rate = $f * (-\log_{10} d^{-1})$ $[NH_3] - c$ f	c	R2	Target NH_3 concentration (mM) 14d sanitation	28d sanitation
34	*Salmonella* spp.*	0.15	−3.0	0.97	<50	<50
	Ascaris suum†	0.0018	0.11	0.87	100	<50
	Bacteriophage MS2*	0.0077	−0.25	0.96	116	75
	ΦX*	0.0017	0.0295	0.87	360	170
24	*Salmonella* spp.*	0.0532	−2.0921	0.88	51	<50
	Ascaris suum†	0.0002	0.0205	0.91	1300	610
	Bacteriophage MS2*	0.0007	0.056	0.83	840	380
	ΦX*	0.0006	0.1103	0.96	890	350

*Assuming pathogen load of 9 $\log_{10}$ cfu/pfu g^{-1} faeces wet weight.
†Assuming pathogen load of 4 $\log_{10}$ eggs g^{-1} faeces wet weight.

distribution would not be more than 5 cm. These tests were performed at 24°C and a higher temperature would increase both the rate of enzymatic degradation of the urea and the distribution of the ammonia within the material. Furthermore, during outbreaks of intestinal diseases the dry matter content of the faeces tends to decrease, improving the rate of distribution of ammonia in the material.

With a urea dose of 4 grams per Peepoo bag, the resulting ammonia concentration ($NH_{3/4}$) is dependent on faecal load and dry matter content of the faeces. According to Emerson *et al.* (1975), the fraction of ammonia found as NH_3 is dependent on both pH and temperature. Addition of 1% urea w/w or more to faeces has been shown to give a stable pH of about 9 for at least two months (Nordin *et al.* 2009, in press). With pH 9 at 24 and 34°C, 35 and 51%, respectively, of the ammonia will be in the form of NH_3. Assuming weight per defecation in the range 100–300 grams and water content in the range 75–99%, ammonia concentration was approximated using an ammonia factor from Swedish default values (Jönsson *et al.* 2005) of 0.711 mole per gram of faeces dry matter. These calculations showed that the NH_3 target concentration for pathogen inactivation (Table 1) can be met at 34°C if the faecal load is not more than 250 g, with a dry matter of 15% or less. At the lower temperature of 24°C, the fractionation into NH_3 is less and at the same time the concentration must be higher to meet the target inactivation (Table 1). The target concentration of 610 mM NH_3 to inactivate *Ascaris suum* eggs at 24°C would only be achieved if faecal load was 100 g.

Increasing inactivation rate with increasing temperature has also been observed for Poliovirus 1 and coliphage f2, with a doubling of reduction rates for each 10°C increase in temperature. However, Poliovirus 1 has been found to be inactivated even at 10°C, at a rate of $-0.1245\,LN\,h^{-1}$, which would exceed the present inactivation target by a wide margin, despite the fact that the NH_3 concentration investigated was only 300 mg NH_3 L^{-1} (18 mM) (Burge *et al.* 1983). At 20°C with higher NH_3 concentrations, the inactivation rates for the same viruses have been shown to increase (Cramer *et al.* 1983). Similar virucidal effects of NH_3 (57 mM) at 21°C as on Polio 1 virus have been observed for Coxsackie virus A and B and an Echo virus, whereas a Reovirus showed more persistence (2 $\log_{10}$ reduction in 24 hours) (Ward & Ashley 1977). Studies on inactivation of *Cryptosporidium parvum* oocysts by NH_3 at 24°C (Jenkins *et al.* 1998) indicate that an inactivation of 6 $\log_{10}$ reduction in 2 weeks can be achieved at this temperature with NH_3 concentrations of 150 mM.

The positive data on reduction of pathogens by ammonia in combination with the distribution of ammonia within the faecal matter indicate that faecal matter collected in a Peepoo bag will be sanitised within four weeks of storage, while at high temperatures the sanitation time will be even faster. During this time, the bags will not degrade to such an extent that there will be a risk of diseases spreading to the environment. Further studies are needed to ensure that there are no or low ammonia loss during the sanitisation period. In addition, a management system

associated with the sanitisation and optimal reuse is needed, e.g. recommendations for closed storage of used bags and application of the bags to the soil for optimal utilisation of the plant nutrients.

CONCLUSIONS

The acceptability of the Peepoo bag among test users was high, especially in a low socio-economic setting with few or no other decent toilet options.

An untrained smell panel was unable to detect any smell from a used bag within 24 h in a 10 m^2 room at 30°C.

In various test media, the bag remained intact during the period required for sanitisation.

After sanitation by the in-bag urea, the Peepoo bag can produce a safe fertiliser within 2–4 weeks depending on the surrounding temperature.

According to these tests, the Peepoo bag is a toilet option at the lowest level of the sanitation ladder, while it is at the top of the pollution ladder as regards providing a safe fertiliser.

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