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Hygiene aspect of treating human urine by alkaline dehydration

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ABSTRACT

Over four billion people are discharging untreated human excreta into the environment without any prior treatment, causing eutrophication and spreading disease. The most nutrient rich fraction is the urine. Urine can be collected separately and dehydrated in an alkaline bed producing a nutrient rich fertiliser. However, faecal cross-contamination during the collection risks to introduce pathogens to the urine. The objective of this hygiene assessment was to study the inactivation of five microorganisms (*Ascaris suum, Enterococcus faecalis*, bacteriophages MS2 and ΦX 174 and *Salmonella* spp) in alkaline dehydrated urine. Fresh human urine was dehydrated in wood ash at 42 °C until the pH decreased to ≤10.5, at which point the saturated ash was inoculated with faeces containing the microorganisms and left open to the air (mimicking stockpiling of the end product) at temperatures of 20 and 42 °C. The bacteria and bacteriophages were inactivated to below the detection limit (100 cfu ml^{-1} for bacteria; 10 pfu mL^{-1} for bacteriophages) within four days storage at 20 °C. *A. suum* inactivation data was fitted to a non-linear regression model, which estimated a required 325 days of storage at 20 °C and 9.2 days at 42 °C to reach a 3 log_{10} reduction. However, the urine dehydration in itself achieved a concentration <1 *A. suum* per 4 g of dehydrated medium which fulfil the WHO guidelines for unrestricted use.

1. Introduction

Human excreta are poorly managed on a global scale. In 2015, the number of people lacking access to basic sanitation was estimated at 2.3 billion. However, the issue is even more serious with the excreta of an estimated 4.5 billion people being discharged into the environment without any treatment (WHO and UNICEF, 2017). Discharging untreated excreta harms the environment by causing eutrophication because human excreta contains plant nutrients (Smil, 2002; Spångberg et al., 2014; Steffen et al., 2015), and harms people, especially children, by spreading disease (WHO, 2006). This issue will not be addressed simply by building more toilets. There is a need for safe toilets that protect the user as well as a system for safely removing, transporting and processing the excreta (Opel, 2012).

The characteristics and content of urine and faeces differ greatly, with the most pertinent difference being, from a managerial point of view, that urine contains most of the plant nutrients excreted while faeces contain the majority, if not all of the pathogens excreted (Höglund et al., 2000). Separate collection of the two fractions means that they can be managed according to their individual composition: urine as a plant nutrient resource and faeces as a potential pathogen-containing fraction. Using urine as a liquid fertiliser poses a logistical challenge since approximately 550 kg yr^{-1} $person^{-1}$ is produced (Vinnerås et al., 2006), which requires either a large storage tank or frequent emptying to a central storage as fertilisers are not applied more often than twice per growing season.

With the objective of minimising the volume of urine, several treatments to concentrate or extract the nutrients in the urine have been studied (Maurer et al., 2006). Since urea is rapidly hydrolysed (degraded into NH_3 and carbonates) already during collection of urine in urine diverting systems (Udert et al., 2003), most studies have focused on recovery from or concentration of hydrolysed urine. Methods for concentrating urine (retaining all nutrients) include reverse osmosis, forward osmosis or membrane distillation, partial nitrification followed by distillation, acidification followed by dehydration (Antonini et al., 2012; Maurer et al., 2006). The recovery of part of nutrients has also been achieved, such as ammonia (NH_3) by air stripping (Antonini et al., 2012), phosphorus with some N *via* struvite precipitation (Pradhan et al., 2017; Udert et al., 2015), or N as NH_4^+ by adsorption on cation exchangers (Kavvada et al., 2017; Tarpeh et al., 2017).

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If the hydrolysis of urea is prevented, urine can be dehydrated with minimal loss of nitrogen, retaining also most of other macro- and micro-nutrients and thus produce a complete fertiliser with a balance reflecting the plant nutrient requirements of the crops (Winker et al., 2009; Randall and Naidoo, 2018). Highly acidic or alkaline conditions, natural or chemical inhibitors as well as temperature and electrolysis can be used for stopping the hydrolysis (Randall et al., 2016). In soils containing clay, lime is often used to increase the pH of the soil to increase the availability of P and alkalinisation of urine to prevent urea hydrolysis seems to be a promising route for urine concentration combining the blocking of hydrolysis and improving the plant nutrient availability. Simha et al. (2018), Senecal and Vinnerås (2017) and Dutta and Vinnerås (2016) have developed an approach that retains NPK by using unhydrolised urine. By this approach, the urine is first alkalinised to prevent urea hydrolysis so that the urine can be dehydrated with minimal loss of nitrogen. The alkalisation can be performed with chemicals, such as lime (Randall et al., 2016), or with alkaline waste products such as wood ash (Senecal and Vinnerås, 2017).

The concept behind the system is that urine would be dehydrated within the toilet, reducing the mass by >90%. Once the pH of the medium has decreased from > 11.5 to < 10.5, mainly due to the capture of CO_2 from the air, it would be replaced with fresh dehydration medium. By placing the dehydration unit inside the bathroom, no extra piping would be required, except for connecting the drying unit to the ventilation. The dried urine (concentrated ten times) can be bagged and collected as a solid to a central fertilisation production unit (Simha et al., 2017). Existing toilets (dry or flush) could be retrofitted with such a system and thus simplify the logistics of handling the urine. As the system would not require a tank, extra plumbing or additional sewer connection for the urine (just good ventilation), the capital costs of implementation may be minimal and the system could be installed virtually anywhere.

Urine inside the bladder of a healthy person is typically pathogen free (Willey et al., 2009), however during excretion of urine in urine-diverting toilets cross-contamination from faeces occurs (Höglund et al., 2000) and bacteria can grow in the biofilm inside the pipes. As faeces may contain pathogenic viruses, bacteria, protozoa and helminths (WHO, 2006), this risk needs to be considered. Diseases that can be emitted *via* the urine are considered a limited risk in temperate countries, but should be considered in tropical climates (however the main risk is still from the faecal cross-contamination) (WHO, 2006). In the WHO (2006) guidelines, the recommended target $\log_{10}$ reduction of indicator pathogens for source-separated urine is 4–5 units (WHO, 2006).

This paper assessed the hygienic health risks involved in using the urine dehydration end-product based on Simha et al. (2018) process by studying the fate of the pathogens in the material after the dehydration process is complete. The experiment was set up to simulate that the last person using the toilet (before the dehydration medium is changed) is contaminating the medium with misplaced faeces, with no time for dehydration of the urine, *i.e.* a worst-case scenario. Hence, the aim was to understand the potential inactivation in the saturated medium after this last user and the effect of storing the alkaline dehydration media, wood ash (and not the effect of the urine dehydration process). In the present study, the inactivation of five microorganisms (three indicators: *Enterococcus faecalis*, MS2 bacteriophage, and ΦX 174 bacteriophage; and two pathogens: *Ascaris suum* and *Salmonella* spp.) was assessed in medium that had already been used to dehydrate urine.

2. Methodology

2.1. Preparation of the saturated ash

Wood ash was prepared as described in Simha et al. (2018). Briefly, fresh human urine from approximately 10 men and women (22–65 years) was collected in sterile 1-L polypropylene containers through-out the study. For each drying run urine from at least three persons was pooled (after storage at 4 °C for at the most 2 days) before each use. The urine composition is presented in detail in Simha et al. (2018). The pH of the urine was increased from <7 to 10.2 ± 0.5 with Amberlite™ IRA410 type–2 resin (Merck Chemicals GmbH, Darmstadt, Germany), which exchanged the Cl^- in urine for OH^-. Ash was produced from burning of birch wood for domestic heating in Uppsala, Sweden. Ash (175 g) was placed in a metal sieve (Ø 0.198 m) in an incubator at 42 °C with two DC 12 V computer fans for ventilation (fan 1: 0.25A, 32 m^3 hr^{-1}, Model AD0812HS-A70 GL; and fan 2: 0.33A, 56 m^3 hr^{-1}, Model AFB0712HB; Delta Electronics, Taiwan). Anion-exchanged urine (100 ml) was added to the ash every 12 h (day and night) until the pH of the ash decreased to ~ 10.5, at which point the medium was considered not suitable for further drying as at a lower pH an increased risk, noted as saturated below. A total of 1600 ml of urine was added to 175 g ash. The microorganisms to be studied were added together with faeces reaching a concentration of bacteria corresponding to >6 $\log_{10}$ cfu g^{-1}, a phage concentration of >8 $\log_{10}$ pfu g^{-1}, and 160 *Ascaris suum* eggs g^{-1}. The addition of the microorganisms together with faeces was to mimic the environmental contamination of urine with faecal cross contamination. Additionally, in other studies by the authors, we have observed that organic material provides a protective environment for microorganisms under hard conditions (data not published).

2.2. Chemical analysis of urine

Total ammonium nitrogen (NH_{TOT}) in fresh urine was analysed using Spectroquant® test kits for ammonia analysis (num.14544, Merck KGaA, Darmstadt, Germany). To hydrolyse the urine (convert urea into NH_4–N), urease enzyme (jack-bean, EC 3.5.1.5; Merck, Germany) were added to urine (5000 U per g assumed urea, according to manufacturer) in a polypropylene tube sealed with a lid with an O-ring. Tubes were incubated at 37 °C for 24 h on a shaker table. The hydrolysed urine was then filtered through a 0.45-μm syringe filter (Sarstedt, Germany) prior to analysis.

The pH and EC of the ash/urine material was measured by diluting 3 g triplicate samples from the mixed with 1:5 distilled water after 1 h rest in capped tubes. pH was measured after 1400 and 1600 ml urine had been added and the EC at the end of the dehydration process. Diluted ash from the pH measurements was returned to the dehydration medium. Based on the electric conductivity, EC (dS m^{-1}), the ionic strength, I (moles m^{-3}), was derived using Equation (1) (Sposito, 2008).

$$log\, I = 1.159 + 1.009 log EC_{1:5} \quad (1)$$

2.3. Estimation of NH_3 in urine

To estimate the NH_3 concentration, the fraction of NH_{TOT} present as NH_3*f*, was first calculated according to Emerson et al. (1975) based on temperature and pH (Eqs. (4) and (5)) and then an Emerson-to-Pitzer conversion model was used (Fidjeland, 2015). Using a Pitzer approach considers also the influence of all ion activity but is thus more complicated to perform. Fidjeland (2015) presented a conversion model (Eqs. (4)–(7)) which is applicable