Research Paper

Rendering fecal waste safe for reuse via a cost-effective solar concentrator

Andrew M. Foote, Emily Woods, Fernando Fredes and Juan S. Leon

ABSTRACT

The goal of this work was to design a cost-effective solar-thermal waste treatment unit and evaluate its ability to render fecal waste safe for reuse. Three trials were conducted from December 2011 through February 2012 in FAVET-Universidad de Chile, Santiago, Chile. The first two trials evaluated helminth viability daily. To calculate the inactivation rate for the solar concentrator unit, the third trial evaluated helminth viability hourly. The solar concentrator met cost requirements of less than US$0.002 per user per day to manufacture. In all three trials, temperatures of treated waste fluctuated from 15°C to 95°C and surpassed temperatures that previous literature has shown to promote pathogen inactivation. There was at least a 2.96 log10 reduction of viable helminth eggs after 1 day in the solar concentrator for all three trials. In the third trial, the inactivation rate ranged from 3 to 6.5 log10/hour^{-1} with a corresponding t_{99} of 0.71–1.55 hours. These results suggest that a solar concentrating unit can meet the need of cost-effectively rendering human feces safe for reuse – helping to prevent diarrheal diseases, and ultimately, saving lives.

Key words | developing countries, helminth, pathogen inactivation, sanitation, solar treatment, waste

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INTRODUCTION

In 2015, over one-third of the world's population lacked access to improved sanitation facilities (WHO 2015). This glaring deficiency results in increased exposure to infectious fecal waste. In developing countries, 90% of untreated feces and wastewater that is disposed of contributes to high rates of diarrheal diseases and even death (WHO 2015). The traditional waste treatment methods are expensive for developing countries. A sewer-based system and treatment plant costs US$50–100 per capita per year, while most residents in low-income countries earn US$2–3 per day (Dodane *et al.* 2012; World Bank Group 2016a, 2016b). New approaches for treating fecal waste are emerging, including large-scale composting. However, many of these methods have not shown continuous success in inactivating resilient pathogens in feces (Mara & Cairncross 1989; Jiménez 2007). Thus, in developing countries, there is a need for more than just safe toilets or human waste containment but rather for safe and affordable collection, treatment, disposal, and reuse of human waste (Nelson & Murray 2008; Uandela *et al.* 2011).

One possible approach to treating feces is via solar-thermal energy. Similar to solar water disinfection, which uses solar thermal and ultraviolet radiation to make water biologically safe to drink, concentrating energy from the sun's rays has the potential to inactivate pathogens in feces. In other fields, concentrating energy from the sun has been effective in solar power plants, cookers, water heaters, and

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water purification (Ciochetti & Metcalf 1984; Grupp *et al.* 1991; Banoni *et al.* 2012). However, there is limited published literature that has examined the efficacy of solar sanitation units to achieve World Health Organization (WHO) criteria for rendering feces safe for reuse (Sossou *et al.* 2016).

One WHO criterion for safe reuse is less than 1 viable helminth egg per gram of total solids. The WHO uses helminth eggs as an indicator due to their resistance to inactivation, particularly with temperature. The prevalence of helminths in sludge varies from 70 to 735 eggs per gram of total solids. Due to these concentrations, the Engelberg quality guideline of a 3 log10 reduction of helminth eggs indicates that a treatment solution would meet the standard of less than 1 egg per gram of total solids (Feachem *et al.* 1983). For the cost of a sanitation system in developing countries, the Gates Foundation has set a standard that end-to-end sanitation service should cost less than US$0.05 per user per day. The goal of this study was to design a cost-effective solar waste treatment unit and evaluate the ability to render fecal waste safe for reuse, as per WHO guidelines. This research provides evidence as to whether a solar waste treatment unit can be used in sanitation systems, decreasing both the amount of untreated waste disposed of and diarrheal risk.

METHODS

Solar concentrator design

While the Gates Foundation standard for end-to-end sanitation service should cost less than US$0.05 per user per day, researchers set a 'stretch goal' to develop a waste treatment technology that could be manufactured at US$0.002 per user per day or just 1/25th the cost of the entire sanitation system. To understand the total price of the system, researchers needed to decide the number of users the system could serve and subsequently the amount of feces one unit could treat. A 50 L drum was selected for experimentation, as it can contain the daily waste of at least 100 people, assuming the average person excretes 0.5 L of feces daily. At a price of US$0.002/user/day, with 100 users and a 5-year lifespan, the total cost of the system to render 50 L of waste safe for reuse in 1 day should be less than US$365.

In order to inactivate pathogens via solar-thermal treatment, the concentrator needed to reach temperatures that have been shown to render waste safe. Previous literature has demonstrated that temperatures upwards of 55°C for over an hour are sufficient for inactivation (Feachem *et al.* 1983; Kato *et al.* 2003; Gantzer *et al.* 2001; Maya *et al.* 2010; Popat *et al.* 2010). Other time and temperature combinations have also proven successful in rendering waste safe; these combinations are referred to as the 'zone of safety'. Due to the diurnal nature of the sun, researchers aimed to design a solar concentrator to reach zone of safety temperatures in 1 day's time (Feachem *et al.* 1983). To reach 55°C for one hour, and above the zone of safety, the concentrator requires about 2 kW of solar power to be absorbed by 50 L of feces. Assuming that a designed system could have an efficiency of 40%, with an average solar radiation of 5 kWh/m^2/day in Santiago, and accounting for estimated heat dissipation in low humidity air, the solar mirror needed to have a surface area greater than 1.5 m^2 of high reflexivity stainless steel.

Pathogen isolation, conditions, and inactivation assessment

Pathogen inactivation was assessed by evaluating the viability of *Toxocara canis* eggs. While *Ascaris lumbricoides* is more commonly used for inactivation, trials took place in Chile, where there is low prevalence of *A. lumbricoides*. *T. canis* is in the same family as *A. lumbricoides* and has shown similar resistance to high temperatures (Maya *et al.* 2010).

Pathogen isolation

T. canis eggs were first isolated and concentrated from fresh canine feces using a modified version of *Standard Methods for Recovery and Enumeration of Helminth Ova in Wastewater, Sludge, Compost and Urine–Diversion Waste in South Africa* (Moodley *et al.* 2008). In brief, the methodology is similar to the EPA and Kato–Katz techniques and uses a combination of filtering, vortexing, and centrifuging. The solutions used in the vortexing and centrifuging were ammonium bicarbonate 1.5 M (Arquimed, Santiago, Chile) and zinc sulfate heptahydrate (Arquimed). The concentration of the solution was determined by enumerating *T. canis* eggs via microscopy in a 50 μL sample. If the final

solution concentration was greater than 100 eggs per mL, it was combined to create a stock solution of *T. canis* eggs in 0.05M H_2SO_4. The solution was enumerated at the beginning of each trial by averaging the total number of eggs in ten 50 μL samples.

Similar to Jensen *et al.* (2009), in order to control the number, location, and sampling of eggs, 1,000–2,000 eggs were placed in 'tea bags' (Jensen *et al.* 2009). Tea bags were made by using a 90-mm diameter nylon disc with a 30-μm pore size (Millipore, Santiago, Chile #NY3009000). The eggs stay inside but were still subject to external environmental conditions through the permeable membrane of the tea bag. Approximately 1,000 eggs from the stock solution for Trial 1 (2.3 mL) and Trial 2 (1.3 mL) and 2,000 eggs for Trial 3 (2.3 mL) were loaded into each tea bag. Each experimental tea bag was assumed to start with the same percentage of viable eggs as the controls had for each respective trial.

Solar concentrator conditions

For each trial, fresh dog feces was gathered from the canine rescue shelter at FAVET-Universidad de Chile and placed into a 50 L steel drum. Tea bags were placed in the center of the drum, laterally and radially. Nylon string was tied to the corner of each bag to aid in finding and pulling of tea bags for sampling periods. The drum was designed with a door along the radial axis for the experiment so samples could easily be taken without disturbing the contents (Figure 1). Five temperature probes with thermocouples (Omega Engineering, Stamford, CT, USA, OM-EL-USB-1, Thermocouples: 5SRTC-GG-K-36) were placed in multiple locations in the drum. For all trials, the solar concentrator was realigned hourly to direct the most solar radiation onto the drum.

Solar radiation measurement

The ambient solar radiation was measured throughout the trials by the HOBO micro station (Omega Engineering, H21-002) with a silicon pyranometer sensor (Omega Engineering, S-LIB-M003). To precisely measure solar radiation being captured by the solar concentrator, the pyranometer sensor was placed on top of the concentrator frame.

Mimic pit latrine conditions

Dog and horse feces were placed into a 30-cm deep hole that was dug next to the solar concentrator. Temperature probes and tea bags were placed in the middle of the mimic pit latrine and an aluminum sheet was placed over the pit to simulate conditions for pathogen inactivation.

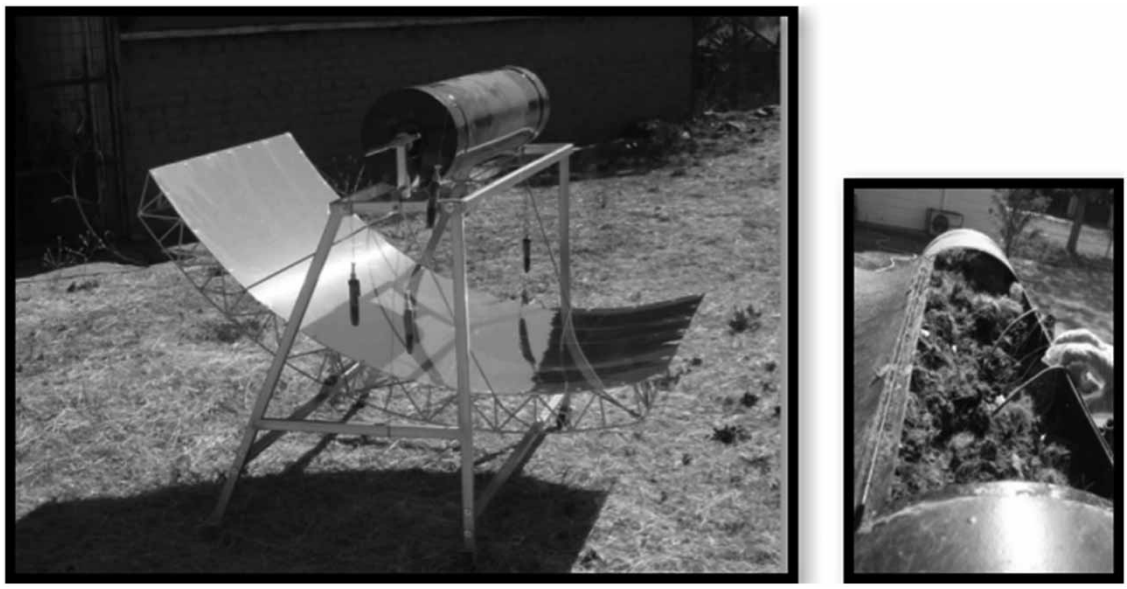

Figure 1 | Left: Solar concentrator with 50 L drum and temperature probes. Right: 50 L drum with radial door, loaded with feces, tea bags, and temperature probes.

Control conditions

Two types of control conditions were maintained. For each trial, at least three tea bags were kept at incubation conditions until all samples for the respective trials were ready for enumeration. Also, stock solution was placed in test tubes without tea bags to examine any possible effects of the tea bag setup on inactivation rates.

Pathogen inactivation assessment: incubation, recovery, and enumeration

Once removed, the tea bags were immediately placed into a 0.05M H_2SO_4 solution and transferred to the laboratory. The tea bags were washed with deionized water to remove any deposited matter. They were then placed in beakers of 0.05M H_2SO_4 solution and incubated at room temperature for 18 days. After incubation, the tea bags were cut open. For enumeration by microscopy, 0.04 mL samples were taken and placed on microscope slides. An egg was classified as viable if it was embryonated with a motile larva. If an egg did not meet this classification, the egg was classified as nonviable. If the total egg count on the slide was less than 100, another sample from the same tea bag was taken and this sample was counted in its entirety. All eggs on the slides for Trials 1 and 2 were enumerated twice to ensure precision. Due to low variability between counts, slides were enumerated only once in Trial 3.

Log-reduction due to experimental conditions was calculated as the difference of the average percentage of viable eggs in control conditions from average percentage of viable eggs in experimental conditions. Viability percentage was determined by the number of viable eggs counted divided by total eggs counted.

This procedure was modified for Trial 3 to estimate egg recovery from tea bags. After incubation, instead of taking a representative sample from the tea bag, the entire contents of the tea bag were emptied into a test tube and 0.05M H_2SO_4 solution was added so that the total volume was between 0.5 and 2 mL. After recording this volume, the solution was stirred and a 0.04 mL sample was taken from the test tube. This sample was then transferred to a slide to be enumerated in the same manner as Trials 1 and 2. With the total eggs counted from a representative sample, the eggs recovered from the tea bag can be estimated by the following formula:

$$R = \frac{C \times V}{0.04} \tag{1}$$

where R is the number of eggs recovered from the bag, C is the number of eggs counted in a 0.04 mL sample and V is the volume measured of total tea bag contents and H_2SO_4.

The average number of eggs recovered per 15 tea bags in Trial 3 was 2,022. The closeness of this value to the estimated 2,000 eggs that were inserted in each tea bag confirms that the tea bag method maintained almost all, if not all, eggs inserted and allowed eggs to be easily recovered.

Inactivation kinetics

Inactivation rate kinetics, or the rate at which pathogens are made inactive, for Trial 3 were analyzed with a model previously used in concave inactivation curves for *A. lumbricoides* eggs and for shouldered survival curves (Harm 1980; Pecson *et al.* 2007). The model includes a coefficient to evaluate the effect of lag before a first order inactivation region:

$$N = N_0\left[1\left(1 - e^{kt}\right)\right]^m \tag{2}$$

$$\text{Lag period} = \frac{\ln(m)}{k} \tag{3}$$

where N_0 is the number of viable eggs at time zero, N is the number of viable eggs at time t, k is the first-order rate constant, and m is an empirical value used to determine the lag period. Inactivation parameters were determined by fitting the model to graphs of ln (N/N_0) and minimizing the residual sum of squares.

RESULTS

Solar concentrator design and costs

The parabolic concentrator trough was constructed of 1.7 × 1 m of highly reflexive stainless steel and focused solar-thermal energy onto a 50 L black aluminum drum (1.0 m radial axis; 0.26 m diameter). The total capital cost of the unit was

approximately US$300, or US$0.60 per capita per year or <US$0.002 per day.

Solar radiation and temperature

For the three trials, the daily solar radiation fluctuation was consistent. The radiation hit a daily peak power between 800 and 950 W/m^2 around 3 to 4 p.m. Due to solar radiation diurnal fluctuation, temperatures inside the drum fluctuated from 15°C to 95°C. All temperature probes for trials exceeded at least one critical temperature for the respective zone of safety time (Gantzer *et al.* 2001; Kato *et al.* 2003; Maya *et al.* 2010). Most days in Trials 1 and 2, the probes recorded multiple values that surpassed critical times and temperatures.

The mimic pit latrine temperatures ranged from 35° to 47°C; these temperatures are uncharacteristically high for pit latrines, which normally range within a degree of ambient temperature (Moe & Izurieta 2003).

Helminth inactivation

The viability of eggs from the tea bags in the control conditions was relatively high, ranging from 91% to 97% across all three trials. The difference between the percentages of the controls in the test tube and the controls in the bag was not statistically significant, and as others have noted, the tea bag is assumed to not have an effect on viability (Eriksen *et al.* 1996; Brewster *et al.* 2003; Jensen *et al.* 2009).

In Trials 1 and 2, the rate of *T. canis* inactivation in the solar concentrator was faster than in the mimic pit latrine (Figure 2). No viable eggs with motile larvae were found in tea bags that underwent 24 hours of treatment in the solar concentrator (2.96-log decrease in viable *T. canis* eggs). While tea bags were only placed in the axis-center of the drum, temperatures were also lowest in this location and thus, inactivation rates can be assumed to be similar or faster in other parts of the drum.

The mimic pit latrine had varying results in the first trial. Some samples from the mimic pit latrine had no motile

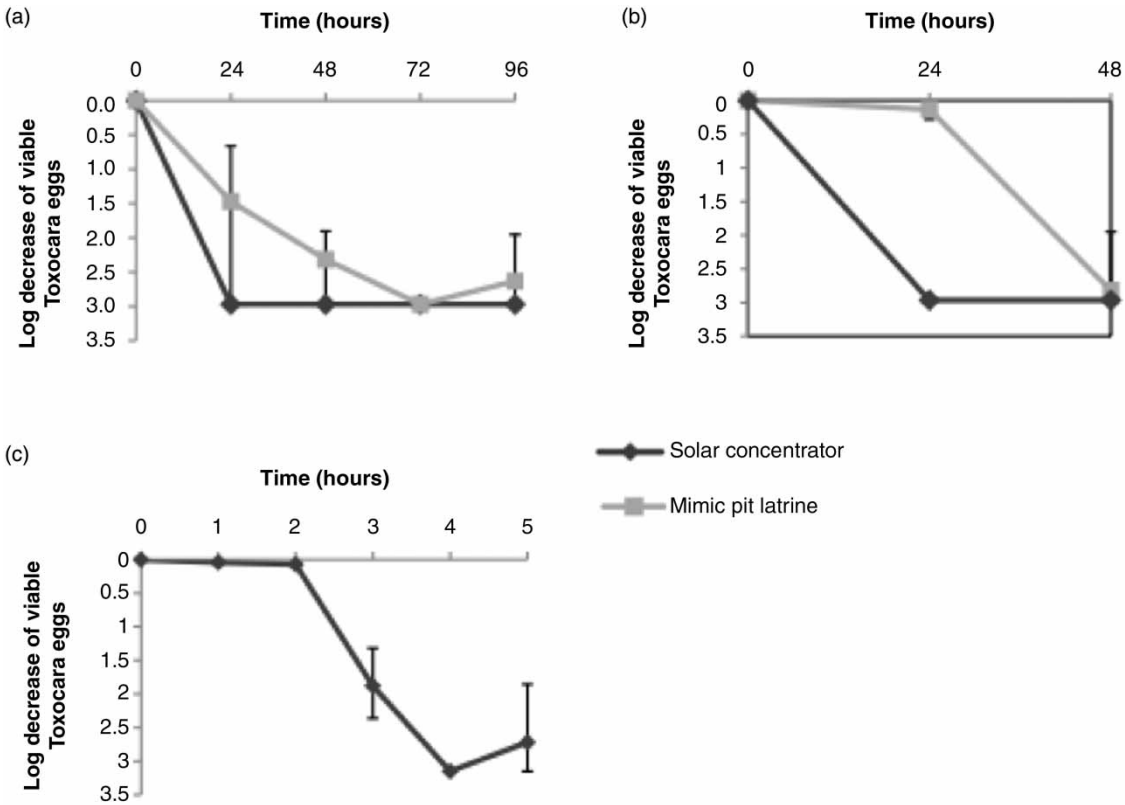

Figure 2 | Log10 decrease of viable *Toxocara canis* at specific durations of exposure to experimental conditions. Darker lines represent samples in the solar concentrator and lighter lines represent samples in the mimic pit latrine for respective trials: (a) Trial 1; (b) Trial 2; (c) Trial 3. No samples were placed in the mimic pit latrine for Trial 3. Data points are the median and error bars represent the range.

larvae after 24 hours and others had motile larvae after 96 hours. Trial 2 had less variability with approximately 70% eggs remaining viable after 24 hours (0.13-log reduction) but an average of 1% eggs remaining viable after 48 hours (2.8-log reduction).

Inactivation kinetics

The lag period for Trial 3 (see Equations (2) and (3) in Methods) was estimated to be between 2 and 3 with a corresponding m ranging from 1,339 to 5,956,538 and an inactivation rate (k) from 3 to 6.5 hour^{-1} with a corresponding t_{99} of 0.71 to 1.55 hours. Because inactivation happened rapidly after the lag period, with only one data point before complete inactivation, there is a range of values for t, k, and m that are statistically feasible. While there is a large range for m, the inactivation rate of 3–6.5 hour^{-1} corresponds with other inactivation rates found for *T. canis* and *A. lumbricoides* at the respective temperatures measured in Trial 3 (Aitken *et al.* 2005; Pecson *et al.* 2007; Maya *et al.* 2010).

DISCUSSION

We aimed to develop a cost-effective solar concentrator that rendered waste safe for reuse per WHO requirements. The solar concentrator inactivated helminth eggs relatively fast; the inactivation rate was 3–6.5 hour^{-1} and all trials had greater than 2.96 log-reductions in 1 day. Other treatment solutions only achieve 1–3 $\log_{10}$ reductions after multiple days, and even weeks, of residency time (Feachem *et al.* 1983; Eriksen *et al.* 1996; Brewster *et al.* 2003; Aitken *et al.* 2005; Sossou *et al.* 2016). We think this fast inactivation of *T. canis* in the solar concentrator was due to the high temperatures of the feces. While helminth eggs are resistant to high temperatures and adverse environmental conditions due to the protective shell with three layers of proteins, temperatures achieved in this study have been shown to inactivate helminths and denature proteins (Jiménez 2007). Denaturing the proteins in these layers lead to the helminth eggs no longer being able to be transmitted and infect others (Jiménez 2007).

When comparing the costs of the solar concentrator to other treatment solutions, the solar concentrator has lower capital costs. Assuming only a 5-year lifespan, the solar concentrator has a cost at $0.60 per capita per year while other solutions of sewer-based treatment plants or even fecal sludge plants assume a 30-year lifespan and range from $1 to $8 per capita per year (Dodane *et al.* 2012). Furthermore, the heat used for pathogen inactivation is harnessed from a free resource, the sun. Other treatments require costly ongoing electricity inputs (~$4 per capita per year) to reduce the biological oxygen demand of fecal sludge (Kato *et al.* 2003; Popat *et al.* 2010; Dodane *et al.* 2012). Reduced biological oxygen demand is often preferred when disposing fecal sludge in the environment (Mara & Cairncross 1989). However, when the transformed feces are reused as soil amendments or burning fuels, reducing the biological oxygen demand can be a disadvantage (Tjandraatmadja *et al.* 2005). With reuse options in mind, a heat-treatment method like the solar concentrator provides both a cost advantage and a benefit for potential resource and cost recovery.

The solar concentrator follows a stepwise approach to waste treatment. Given its current size, approximately 500 solar concentrators would be required to safely treat waste from 50,000+ users. Operating this many solar concentrators is an impractical solution to address the needs of large populations; however, the cost-effective concept of using solar-thermal energy to treat human waste is still valid. When scaling a treatment solution, previous research has noted the importance of taking a stepwise approach – starting small and modular and building to a more industrial-level system (Galli *et al.* 2014). The step-wise approach is modeled to be more inherently cost-effective, as sewer-based systems are not designed to meet their capacity until the end of their 30-year lifespan (Maurer 2009). Given a redesign, a solar-thermal process has the potential to meet the waste treatment needs of rapidly expanding urban areas.

The methodology developed and used in this study appeared to overcome previous limitations in helminth inactivation research. For example, when calculating log-reductions and inactivation rates, previous research has commonly noted two limitations: (1) log-reductions could not be calculated because researchers could not confirm the amount of pathogens in the feces before the treatment intervention; and (2) the helminth isolated may not model helminth found in excreted feces, as eggs were taken directly from a female worm in the intestines of a pig; thus, they had not yet hatched

and existed in feces (Jensen *et al.* 2009; Berendes *et al.* 2015). We overcame the first limitation by seeding the feces with a known number of helminth eggs in tea bags. The high recovery rate from the tea bag and control setup confirmed that eggs were not lost or inactivated in the experimental procedure. For the second limitation, while this study did not use *A. lumbricoides* or *A. suum*, we did isolate *T. canis* from excreted feces. These isolated *T. canis* eggs were then reinserted into their natural environment via the tea bag method. Reinserting pathogens into an environment where they already existed adds validity to the method. By overcoming these limitations, we believe that this methodology allows researchers to produce more verifiable and accurate results when conducting pathogen inactivation studies.

One limitation in this study was that the fieldwork was conducted on a university campus; thus, we were not able to create an appropriate mimic pit latrine. The constructed pit latrine could only be 30 cm deep whereas the typical depth of pit latrines ranges from 2 to 6 m (Moe & Izurieta 2003). Solar radiation has been shown to increase soil temperatures at depths of less than 0.5 m due to heat absorption (Florides & Kalogirou 2005). The mimic pit latrine recorded temperatures 20°C greater than ambient temperature whereas a typical pit latrine ranges within 1–3 degrees of ambient temperature (Moe & Izurieta 2003). We hypothesize that the higher temperatures of 40–50°C led to faster inactivation of *T. canis* than in a typical pit latrine, which has viable helminth eggs present after 6 months. Future studies conducting temperature inactivation experiments with a mimic pit latrine should consider the site of their research and more importantly the depth of the pit latrine to ensure an accurate model.

CONCLUSION

The solar concentrator achieved pathogen inactivation rates that accord with the WHO standard for waste to be safely reused. While in its current design, the solar concentrator is a small-scale waste treatment solution, the concept of leveraging free solar-thermal energy shows potential to be a cost-effective approach to rendering waste safe. In testing other waste treatment solutions, future pathogen inactivation studies can readily adopt the methodology used in this study. Organizations operating sanitation services in large populations or planning to start sanitation services can use this research to explore solar waste treatment and meet the need of cost-effectively rendering human feces safe for reuse – helping to prevent diarrheal diseases and ultimately, saving lives.

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