

PERFORMANCE OF SOLAR GREENHOUSE SAND DRYING BEDS IN FECAL SLUDGE HEATING AND DRYING AND INACTIVATION OF *OPISTHORCHIS VIVERRINI* EGGS DURING WINTER IN THAILAND

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Abstract

Inadequate fecal sludge treatment is contributing to the high prevalence of *Opisthorchis viverrini* (OV) infections in northeast Thailand. Two configurations of solar greenhouse drying beds were assessed and compared against a conventional covered (open-air) sand drying bed during two experimental rounds. The objectives were to compare sludge heating and drying rates among the beds and to identify factors associated with inactivation of OV eggs. The sludge temperatures (°C) in the greenhouse (daily $\bar{x} \pm \text{SD}$ = 32.8 $\pm$ 1.8, 28.4 $\pm$ 2.9) were higher than the covered open-air bed (27.0 $\pm$ 1.8, 25.6 $\pm$ 2.7) with 150-250 min per day >40°C during sunny days, while sludge temperatures in the open-air bed never exceeded 40°C. The addition of a solar-heated water system underneath the sand drying bed increased the sludge temperature (°C) further (33.9 $\pm$ 1.8, 30.0 $\pm$ 2.3; 350 to 450 minutes per day >40°C). With proper ventilation and air circulation, the solar greenhouse sand drying beds (first-order drying rate, k = 0.092, 0.193) were also able to dry sludge at a faster rate than the open-air bed (k = 0.076). Sludge dryness, sludge temperature, and time were significantly associated with increased OV inactivation. Solar irradiance and air relative humidity were identified as factors associated with sludge drying. These results highlight the importance of balancing enclosure to increase sludge heating with ventilation to reduce relative humidity in order to optimize OV egg inactivation. Solar greenhouse sand drying beds may provide a low-cost, low-technology option for fecal sludge management in tropical Thailand.

Keywords: Fecal sludge management, human excreta, parasites, solar radiation

Introduction

Thailand has rapidly achieved nearly universal access to basic sanitation at the household level, increasing access from 1% in 1960 to greater than 95% in 1999 (Trémolet and Binder, 2013). However, the contained fecal sludge (FS) must also be safely managed (UN, 2016) via a functional fecal sludge management (FSM) service chain, including

containment, collection, transportation, treatment and disposal of FS (Strande *et al.*, 2014). Thailand's FSM service chain is deficient in treatment (Taweesan *et al.*, 2017). Despite the legal requirement for FS vacuum trucks to dispose of their contents at treatment plants in Thailand, most municipalities do not have treatment facilities available (Suebsoh and

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Charerntanyarak, 2009). Around 70% of the 19 million cubic meters of FS annually collected in septic tanks and cesspools across Thailand is not treated and gets disposed of illegally and/or inappropriately in waterways, farmland, and landfills (Chokewinyoo, 2008; USAID, 2010). Such illegal and inadequate FSM has important public health ramifications.

Opisthorchis viverrini (OV), or the southeast Asian liver fluke, is a helminth endemic to Thailand, Laos, Cambodia, and Vietnam, with highest prevalence (15 to 20%) in areas of northeast Thailand (Suwannatrai *et al.*, 2018). OV infection is highly associated with cholangiocarcinoma, as well as many other diseases of the bile duct, liver, and gall bladder (Sripa *et al.*, 2010). As part of its complex life cycle, the trematode produces eggs that pass from the bile to the feces, which can hatch miracidia when in fresh water (Fried *et al.*, 2011). Inactivating OV eggs via effective FS treatment is an important public health measure to reduce the incidence of cholangiocarcinoma and other diseases caused by OV in Thailand (Mayer and Fried, 2007; Kaewkes *et al.*, 2012).

A low-cost, low-technology solution would be ideal for improving availability of FS treatment facilities in Thailand, beyond the commonly-used anaerobic digesters, co-disposal in sanitary landfills, and sludge drying beds (Taweesan *et al.*, 2017). Large-scale solar greenhouses are in operation in many places across the world, including the Americas and Europe (Meyer-Scharenberg and Pöppke, 2010; Socias, 2011). Solar drying, in which a greenhouse is used to accelerate evaporation from a sand drying bed or concrete basin, has emerged as a possible solution to both dewatering and treatment, especially in regions where solar radiation is abundant (Bennamoun, 2012; Mathioudakis *et al.*, 2013; Kurt *et al.*, 2015). In addition, solar drying has low operational and energy costs and less complex procedures, requiring minimal expertise and equipment, which makes it one of the most economically viable options for FSM in small and rural communities (Singh *et al.*, 2017). Solar drying has been shown to increase pathogen removal and decrease drying time compared to conventional drying beds (Salihoglu *et al.*, 2007; Mathioudakis *et al.*, 2009; Shanahan *et al.*, 2010; Seck *et al.*, 2015). Temperature in the sludge is one of the most critical factors for reducing bacteria, viable nematode eggs (Gantzer *et al.*, 2001) and helminths (Maya *et al.*, 2012; Echaubard *et al.*, 2017; Boueroy *et al.*, 2019). However, while many studies have monitored pathogens, fewer studies have closely monitored sludge temperatures in solar sludge drying to demonstrate the role of heat in treatment (Seginer and Bux, 2005; Salihoglu *et al.*, 2007), and

few have demonstrated its potential in tropical climates (Cofie *et al.*, 2006; Seck *et al.*, 2015) or examined fecal sludge from on-site treatment rather than from wastewater (Belloulid *et al.*, 2017; Ozdemir *et al.*, 2020; Ameri *et al.*, 2020).

Thus, the objectives of this study were to 1) provide experimental data of heating and drying performance by solar greenhouse sand drying beds on fecal sludge collected from on-site containment in a tropical climate, 2) investigate whether solar greenhouses and solar-heated heat transfer pipes could improve the heating and drying performance compared to open-air sand drying beds and 3) identify sludge performance factors association with OV inactivation in the sand drying beds.

Materials and Methods

Research Facility and Experimental Operation

Three pilot-scale sand drying beds were evaluated at an experimental fecal sludge treatment plant in Khon Kaen, Thailand (N16°27'43.5'', W102°48'22''). The sand drying beds were identical in size (1.5×2.5 m) and composition (coarse sand on top of gravel on top of perforated drainage pipe). Sand drying bed A, the control, had a conventional open-air roof approximately 1.5 m above the bed. Sand drying beds B1 and C1 had greenhouses (2.5 m height) with translucent panels built around them. Bed C1 also added a solar-heated (via 3×2 m inclined plate solar collector) circulating pipe system, similar to Salihoglu *et al.* (2007) under the sand (1-inch diameter iron pipe spaced at 15 cm intervals), as shown in Figure 1. The solar collector had 3-inch diameter iron pipes painted black enclosed within an insulated case with a plastic cover, inclined 10 degrees towards the southern sky. Effluent from the sand drying beds drained into underground septic tanks. The two solar sand drying beds (B1 and C1) had two active ventilation fans (influent and effluent) with an exchange rate around 5 m³/m²/h and an overhead circulating fan for circulation of air within the greenhouse (only installed for Round 2) with a mixing rate around 10 m³/m²/h. Exhaust fans were turned off at 10:00 am and turned back on at 2:00 pm daily to allow temperatures within the greenhouse to increase during peak solar radiation hours. The overhead fan was turned off at 10:00 am and turned back on at 1:00 pm. The water pump, which pumped the solar-heated water under the C1 bed operated from 10:00 am to 5:00 pm. Each experimental round was terminated once the soil moisture content reduced to 80-90 percent total solids (%TS). Round 1 (November 2017) lasted 26 days; Round 2 (January 2018) lasted 11 days.

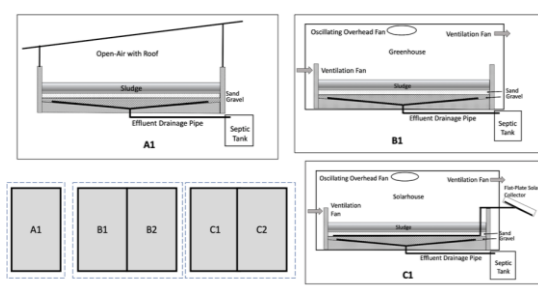


Figure 1. Cross sections of the pilot scale research facility in Khon Kaen, Thailand

Fecal Sludge Characteristics

FS, collected from local residential and commercial customers, was deposited into the sand drying beds from a five-cubic-meter vacuum truck in the two experimental rounds. The hydraulic loading on the bed was around 25 cm (Heinss *et al.*, 1998; Dodane and Ronteltap, 2014). A composite sample of the FS from the vacuum truck was collected and analyzed for biological oxygen demand (BOD), total solids (TS), volatile solids (VS), total Kjeldahl nitrogen (TKN), total phosphorus (TP), copper (Cu), cadmium (Cd), lead (Pb), and fecal coliform (FC). The samples were collected in a plastic bottle without preservative, placed in a cooler with ice, delivered to the laboratory within 24 h, and analyzed using Standard Methods (APHA WEF, 2012). Results are reported in Table 1.

Monitoring of Fecal Sludge Temperature and Moisture Content

FS temperature was continuously monitored and logged at 5-min intervals using Hobo U23 temperature probes and data loggers. The temperature probe was placed 5-10 cm from the corner of the sand drying bed at the bottom of the sludge. As drying created cracks in the sludge, the probes were covered in sludge again.

Moisture content (recorded as volumetric water content) was measured and recorded daily between 9:00 am and 10:00 am using a Delta-T HH2 soil moisture meter and WET soil moisture probe at five locations (four corners and center). In addition, samples were periodically collected and analyzed

for %TS using Standard Methods (APHA WEF, 2012). Analysis of %TS was used to confirm estimates of %TS derived from moisture content readings, as described below.

OV Sampling and Analysis

OV eggs used in this study were obtained from the Safe Food, No Worms Project under the Fluke Free Thailand Project. Approximately 15-20 OV eggs in 0.85% saline solution were pipetted into an Eppendorf tube (1.5 ml). Twenty Eppendorf tubes were then pinned down into each sand drying bed (A, B1, and C1). Each day, one Eppendorf tube was removed from each bed, and the OV eggs were counted and classified as hatched (open) eggs, deformed (unviable) eggs, and viable (alive) eggs. The first two categories were then combined into a single classification of “inactivated.” Identification was made using light microscope with Formalin-Ether Concentration Technique. Due to limited access to OV eggs, OV monitoring was only conducted for Round 1.

Monitoring of Environmental Conditions

Air temperature and relative humidity were monitored continuously at 5-min intervals one meter above the sand drying bed in each experimental setup and also in ambient conditions (located nearby the beds under shade) using Omega OM-141 RH/temperature data loggers. Solar radiation was estimated from light intensity, which was monitored using a Hobo UA-002 light intensity data logger at 5-min intervals.

Statistical Analysis

All data management and statistical analyses were conducted with Microsoft Excel or Stata 14 (licensed to Faculty of Public Health, Khon Kaen University).

Air Temperature and Relative Humidity. Daily means (midnight to midnight) of air temperature and relative humidity were computed for each sand drying bed (A, B1, and C1) and ambient conditions. Descriptive statistics were calculated using the daily means. Comparisons of air temperatures between sand drying beds were made by computing the F-ratio test statistic from a one-way ANOVA test and tested against a 0.05 significant level with *post*

Table 1. Physical, chemical, and biochemical parameters of fecal sludge loaded onto drying beds

Parameter	BOD (mg/L)	TS (mg/L)	VS (mg/L)	TKN (mg/L)	TP (mg/L)	Cu (mg/L)	Cd (mg/L)	Pb (mg/L)	FC (MPN/ 100 mL)
Round 1	6,300	40,825	32,950	1,688	488	9.86	0.043	ND*	1.4×10^7
Round 2	746	3,585	2,215	317	34.6	1.04	0.006	ND*	1.6×10^4

* ND = not detected. Method detection limit = 0.10 mg/L

hoc tests conducted using Tukey's Honest Significant Difference (HSD) test (Tukey, 1949).

Sludge Temperature. Daily mean sludge temperatures (midnight to midnight) in each sand drying bed (A, B1, and C1) were computed. Descriptive statistics were calculated for the daily mean sludge temperatures. Additionally, the number of minutes per day greater than 40°C in the sludge was computed by counting the number of readings greater than 40°C multiplied by 5 min. Comparisons between beds were conducted using same methods as air temperature.

Sludge Moisture Content and %Total Solids. %TS, as a mass ratio, was calculated using Equation 1 and the median of the five daily sludge moisture readings (%MC). This relationship was confirmed by regressing computed %TS from equation 1 to 19 laboratory measurements of %TS ($R^2 = 0.88$).

$$\%TS = (100 - \%MC) / (100 + \%MC) * 100 \quad (1)$$

First-Order Drying Rates. The remaining water content, W , was computed as $W = 100 - \%TS$. A first-order decay (exponential) model was fitted to an average experimental round drying rate, k , with units d^{-1} as found in Equation 2.

$$\frac{dW}{dt} = -kt \quad (2)$$

Daily drying rates were computed as the difference between the natural logs of centrally-weighted average of W on consecutive days. These values were used to determine factors associated with increased drying rates, as described below.

Solar Irradiance. Daily solar irradiance was estimated from measured light intensity using the spectral sensitivity (193 lum/W) of the UA-002 device as determined by correlating light intensity

readings during clear sky conditions to clear sky irradiance derived by the ASHRAE clear-sky irradiation model (Machler and Iqbal, 1985).

Sludge Loading Rate. The annual sludge loading rate (SLR) for each drying bed was computed using the initial total solids concentration (TS_0), in mg/L; area (A), in m^2 , and time to reach 90% total solids (t_{90}), in days (Equation 3):

$$\frac{TS_0 * 1000 * 365}{A * t_{90} * 10^6} = SLR \quad (3)$$

Factors Associated with Drying Rate. A multiple linear regression model was used to assess association of factors with the daily drying rate in each bed. Daily drying rates from all three sand drying beds and two rounds ($n = 93$) were compiled into a single database for regression. Solar irradiance, average daily air temperature, average daily relative humidity, average daily sludge temperature, water content, and ambient relative humidity were considered as possible factors. The value for each factor from the previous day was used since soil moisture was measured in the morning except for water content (same day). Hierarchical block-wise entry was used to construct the model, and a significance level of 0.05 was used.

Factors for OV Egg Inactivation and Probability of Inactivation. Multiple logistic regression was used to assess factors associated with OV egg inactivation. Two factors, cumulative average %TS and the interaction effect of time with cumulative average of the median sludge temperature, were chosen as the predictive variables for the outcome of interest (egg inactivation) using the forced entry method ($n = 207$). The multiple logistic regression model was then used to predict OV inactivation in Rounds 1 and 2.

Table 2. Summary statistics for daily mean air temperatures and relative humidity

Parameter	Ambient	Control (Open-Air)	Building B (Greenhouse)	Building C (Greenhouse + Solar)	F-ratio (p-value)
Round 1 (n = 26)					
Temperature (°C)					42.5 (<0.001)
Mean (SD)	27.8 (1.9)	29.4 (2.3)	35.4 (2.7)	35.1 (2.9)	
Min:Max	23.3:31.0	23.5:32.6	27.2:39.7	26.6:39.7	
Rel. Humidity (%)					
Mean (SD)	63.2 (4.9)	62.0 (4.7)	60.6 (5.1)	60.4 (5.2)	
Min:Max	50.2:69.3	50.8:68.6	48.0:68.5	49.2:69.4	
Round 2 (n = 11)					
Temperature (°C)					6.78 (0.004)
Mean (SD)	25.0 (3.0)	27.1 (3.4)	32.2 (4.3)*	32.2 (4.1)*	
Min:Max	19.0:27.8	20.3:30.3	24.5:35.9*	24.5:35.9*	
Rel. Humidity (%)					
Mean (SD)	57.2 (3.0)	62.3 (3.2)	59.4 (3.7)*	57.4 (3.8)*	
Min:Max	53.5:62.1	55.4:66.4	50.9:64.2*	47.7:61.8*	

* = Day 1 data was excluded from Building B and Building C because exhaust fans did not operate, generating high temperatures and relative humidity, so $n = 10$ for these summary statistics

Results and Discussion

Air Temperature

Air temperatures in the three beds were significantly different (F-ratios = 42.5, 6.78, Table 2). The air temperatures within the greenhouses were several degrees higher (approximately 5 to 6°C, on average, in both rounds) in the greenhouses compared to air temperatures above the open-air sand bed. However, air temperatures within the two greenhouses (Buildings B and C) were not significantly different (*post hoc* tests showed p-value between buildings >0.50). Therefore, any differences in sludge temperature between Buildings B and C were not likely due to differences in heating from the air.

Sludge Temperature

Daily sludge temperature within the greenhouse (B) were 5.8 and 2.8°C higher, on average, in Rounds 1 and 2, respectively, than the control (Table 3). The addition of the solar heater (Building C) further increased daily sludge temperature by 1.1 and 1.6°C, on average. During a typical sunny day, temperatures in the sludge reached 35 to 40°C in the greenhouse (B) and 40 to 50°C in the solarhouse (C) (Figure 2). The higher sludge temperature in the solarhouse can be attributed to the addition of solar-heated water beneath the sand drying bed because the air temperatures in Buildings B and C were nearly identical.

Not only were mean and peak sludge temperatures in Building C > Building B > Building A, but length of time per day where the sludge temperature exceeded 40°C also followed the same order. During sunny days (solar irradiance 15 to 22 MJ/m²/d), the greenhouse maintained sludge temperatures greater than 40°C for around 150 to 250 min daily (Figure 3). However, the solarhouse maintained those temperatures for 350 to 450 min daily. On cloudy days (solar irradiance 5 to 15 MJ/m²/d), the greenhouses were less effective at heating sludge, achieving 0 to 150 min per day greater than 40°C. The sludge temperature in the

open-air covered sand drying bed (A) did not achieve 40°C at any point during both experimental rounds.

The ability of the greenhouses to raise sludge temperatures above 40°C for two to eight hours on any sunny day is a promising result for bacteriological and parasitological control. Previous studies have demonstrated that temperature, pH, and

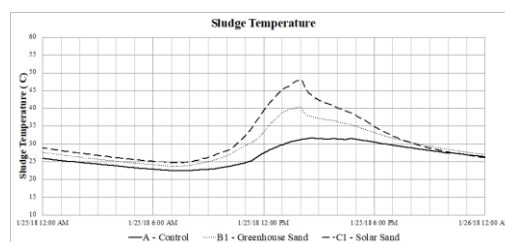
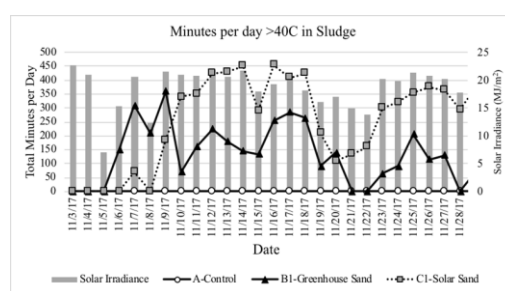
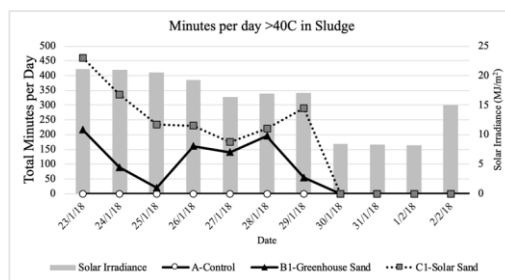


Figure 2. Example graph of daily sludge temperature (January 25, 2018)



(A)



(B)

Figure 3. Time per day where sludge temperature exceeded 40°C with solar irradiance in (A) Round 1 and (B) Round 2

Table 3. Summary statistics for daily mean sludge temperatures

Parameter	Control (Open-Air)	Building B (Greenhouse)	Building C (Greenhouse + Solar)	F-ratio (p-value)
Round 1 (n=26)				
Mean (SD)	27.0 (1.8)	32.8 (1.8)	33.9 (2.8)	73.5 (<0.001)
Min:Max	23.6:29.7	29.1:35.6	28.0:38.2	
Round 2 (n=11)				
Mean (SD)	25.6 (2.7)	28.4 (2.9)*	30.0 (2.3)*	7.97 (0.002)
Min:Max	20.8:28.3	23.3:31.4*	25.9:33.4*	

* = Day 1 data was excluded from Building B and Building C because exhaust fans did not operate, generating high temperatures and relative humidity, so n = 10 for these summary statistics

dryness are the critical factors to inactivating pathogens (Gantzer *et al.*, 2001; Maya *et al.*, 2012). While temperatures of 40 to 45°C inactivate a significant proportion of nematode eggs, the eggs can remain viable for 8 to 16 months at temperatures around 25°C (O'Donnell *et al.*, 1984; Gantzer *et al.*, 2001). Increased mortality in OV eggs occurs at temperatures of 35 to 40°C (Echaubard *et al.*, 2017; Boueroy *et al.*, 2019). Based on previous research, it is reasonable to assume that 50% of viable helminth larvae are inactivated from 180 min of contact time to temperatures between 40 and 50°C (Maya *et al.*, 2012). For temperatures of 60, 70, and 80°C, inactivation times for OV reduce to 15, 10, and 5 min (Boueroy *et al.*, 2019). These greenhouses were able to heat sludge to temperatures of 40 to 50°C. However, the sludge temperature is highly dependent on solar irradiation. During extended periods of cloudy weather, such as while experiencing a monsoon trough in the rainy season, temperatures favorable to inactivation will not be achieved and sludge must be held longer.

Sludge Drying and Related Factors

The sludge achieved an estimated 80% TS in 17 to 24 days during Round 1 and 6 to 11 days in Round 2 (Figure 4). The shorter drying time in Round 2 can be primarily attributed to the lower concentration of total solids in Round 2. The higher water content of Round 2 allowed the water to quickly infiltrate through the sand and gravel filters and resulted in a thinner layer of biosolids. Worldwide, the characteristics of FS are highly variable and dependent on the type of containment, on-site storage duration, emptying practices, quality of containment construction, and temperature, among other things (Strande *et al.*, 2014). Therefore, monitoring sludge moisture is an important component of sand drying bed operation. In addition, the variability in metals and nutrients (Table 1) must be considered in the reuse of treated FS, such as land application or compost (Bassan, 2014; Ozdemir *et al.*, 2020).

In Round 1 the solar-heated greenhouse (C) was comparatively effective at drying when compared to the control (A), as demonstrated by the first-order drying rates (Table 4). The greenhouse (B), however, was less effective at drying the sludge in Round 1. In Round 2, however, the drying rates were higher in the greenhouses than the open-air

bed, and Building C was more effective than Building B.

In both Buildings B and C, the drying rates increased from Round 1 to Round 2. In Round 1, the overhead circulating fans were not yet operational. The improvement in drying rates from Round 1 to Round 2 within the greenhouses demonstrates the impact of the overhead fans. On the other hand, the variability in the drying rate of the open-air control came from natural wind blowing across the sand bed. Periods of high wind speeds from seasonal changes helped the open-air system to dry faster. These periods occur occasionally during winter in Thailand (November to February). One option to take advantage of these natural conditions and save energy would be to add hinges to the greenhouses so that they could be opened during favorable wind conditions and closed later.

According to the multiple linear regression model, three factors were significantly associated with the daily drying rate of the sludge (Table 5). Solar irradiance was positively associated with drying rate. Air relative humidity and water content were negatively associated with drying rate. The drying rate of sludge has been shown to depend on

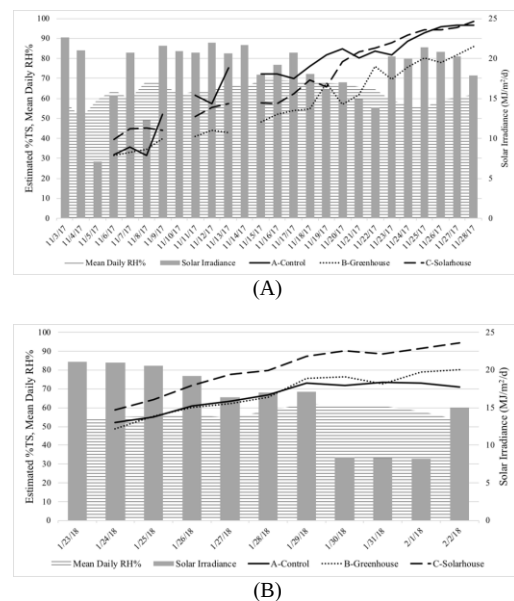


Figure 4. Sludge drying trends with environmental conditions in (A) Round 1 and (B) Round 2

Table 4. First-order drying rates (k) and coefficient of determination (R²)

k (R ²)	Round 1 (November)	Round 2 (January)
Building A (Open-Air)	0.095 (0.827)	0.076 (0.801)
Building B (Greenhouse)	0.050 (0.832)	0.092 (0.907)
Building C (Greenhouse + Solar)	0.094 (0.718)	0.193 (0.952)

Table 5. Regression coefficients from final multiple linear regression model for factors significantly associated with daily drying rates in sludge drying beds (n = 93)

Factor	Coefficient (β) (95% CI)	Standard Error	p-value
Solar Irradiance (MJ/m^2)	0.0048 (0.0000-0.0095)	0.0024	0.05
Air Relative Humidity (%)	- 0.0059 (- 0.0112- - 0.0006)	0.0027	0.03
Sludge Water Content (%)	- 0.0034 (- 0.0047- - 0.0021)	0.0007	<0.001
Constant	0.5002 (0.1582-0.8421)	0.1721	0.005

Table 6. Adjusted odds ratios of sludge drying bed factors significantly associated with OV egg inactivation according to multiple logistic regression model (n = 207)

Factor	Adjusted Odds Ratio (aOR) (95% CI)	Standard Error	p-value
Soil Total Solids (%)	1.041 (1.003-1.080)	0.0197	0.04
Sludge Temperature ($^{\circ}\text{C}$) x Duration (days)	1.016 (1.010- 1.023)	0.0032	<0.001
Constant	0.030 (0.0029-0.321)	0.0366	0.004

air temperature, relative humidity, solar radiation, and air exchange rate (Seginer and Bux, 2005). In our model, air temperature was not significantly associated with drying rate. One possible explanation for this result is that increased air temperature was generally the result of sealing the greenhouse shut, which counteracted the effects of increased temperature by maintaining higher relative humidity. While active ventilation is required in solar greenhouse sand drying beds (Seck *et al.*, 2015), the exchange of air also removes the heat trapped by the greenhouse. Thus, there is a tradeoff between reducing humidity (air exchange) and increasing heat. This study's approach was to cycle the active ventilation fans off during peak solar radiation hours (10:00 am to 2:00 pm). Accordingly, sludge temperatures were significantly increased while drying rates were generally equal to or better than the control. Since solar irradiance and relative humidity are important determinants of sludge drying, according to these results, the seasonality of these factors in Thailand is an important consideration. Extended periods of cloudiness and rain, particularly at the end of the rainy season, will substantially slow sludge drying rates for all sand bed types.

Sludge Loading Rates

Sludge loading rates, computed from actual drying times and initial solids composition, were 29 to 234 $\text{kg}/\text{m}^2/\text{yr}$ for the open-air control, 32 to 173 $\text{kg}/\text{m}^2/\text{yr}$ for the greenhouse and 44 to 209 $\text{kg}/\text{m}^2/\text{yr}$ for the solar-heated greenhouse. These loading rates are consistent with other sand drying beds in tropical climates (Cofie *et al.*, 2006; Dodane and Ronteltap, 2014; Seck *et al.*, 2015).

OV Inactivation and Related Factors

In total, 207 OV eggs were collected and analyzed with 76.3% inactivated. Three factors were identified from the logistic model as associated with OV egg inactivation: sludge dryness, sludge temperature, and time (Table 6). Each 1% increase of sludge TS was associated with a 4% increase in OV egg inactivation after adjusting for time and sludge temperature. Temperature and dryness have been identified as influential determinants for inactivation of OV and other helminth eggs (Maya *et al.*, 2012; Echaubard *et al.*, 2017). Because solar greenhouse sand drying beds sacrifice air circulation to achieve higher temperatures, it is important to carefully balance these two factors to optimally reduce relative humidity and increase air temperature. One possibility would be to have either very large windows or fans that are opened/operated outside of peak solar radiation times. The addition of the solar-heated water circulation also shows promise, as it increased sludge temperature without negatively affecting relative humidity.

Using the multiple logistic regression model, the predicted probability of OV egg inactivation, given the sludge dryness, temperature, and time, was estimated for Round 1 (Figure 5(A)). OV egg inactivation was also similar between all three beds for the single round of observation. The difference between each sand bed is not significant. The model was also used to estimate the OV egg inactivation probability for Round 2, during which no eggs were sampled (Figure 5(B)). Due to improved air flow from the addition of an overhead oscillation fan in Round 2, the drying rates in the greenhouses increased and a trend in improved inactivation is demonstrated among the greenhouses.

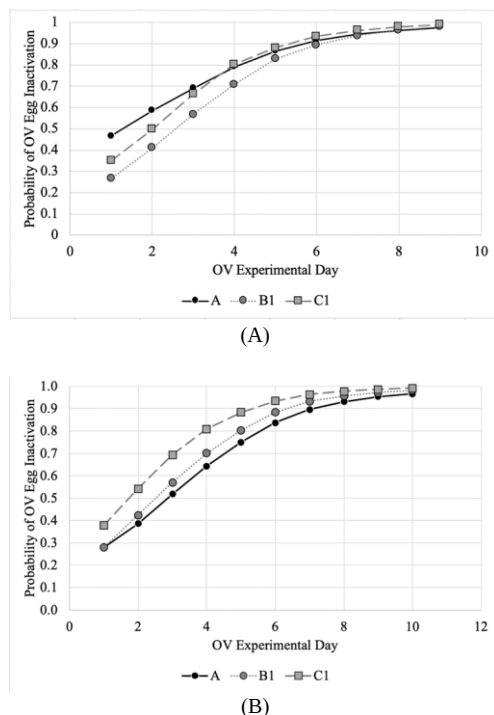


Figure 5. Probability of OV egg inactivation using multiple logistic regression ($n = 207$) calibrated to results from Round 1 (A) and used to predict estimated inactivation for Round 2 (B)

Implications for FS Treatment in Thailand

Solar greenhouses are not always effective solutions to pathogen treatment (Paluszak *et al.*, 2012). Other solutions, such as co-composting and anaerobic digestion, must also be considered (Gantzer *et al.*, 2001; Singh *et al.*, 2017). However, sand drying beds are already commonly used for FS dewatering in rural Thailand. The low cost and familiarity of solar greenhouse sand drying beds makes them the most viable solution to adapting existing systems and implementing new procedure until sufficient funding and technological training are provided for other solutions.

Conclusions

Solar greenhouse sand drying beds are presented in this study as a practical solution for drying and treating fecal sludge in rural Thailand and other tropical countries. The solar greenhouse sand drying beds significantly increased the sludge temperature relative to the conventional open-air sand drying bed. With proper ventilation and air circulation, the greenhouses increased drying rates. OV egg inactivation was shown to be associated with sludge dryness, sludge temperature, and time. Sludge

drying rate was shown to be associated with (high) solar irradiance and (low) air relative humidity. Therefore, optimum operation of solar greenhouse sand drying beds must balance increasing sludge temperature via enclosure and reducing air relative humidity via ventilation. The goal should be to optimize enclosure during periods of high solar irradiance and maximize ventilation during other times. These results demonstrate that solar greenhouse sand drying beds are equivalently effective to marginally better at inactivating OV eggs compared to conventional open-air sand drying beds. Future research should examine the optimization of operational procedures (fan speeds, exchange rates, and timing) to further improve heating, drying, and OV egg inactivation in solar greenhouses.

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