ABSTRACT: The compost withdrawn from a composting toilet still contains pathogens and therefore requires a post-treatment unit to treat the compost prior to reuse. A quantitative microbial risk assessment Monte Carlo was conducted to evaluate the risk of infectious diseases and the length of time for the post-treatment. The accidental ingestion of compost (0.5–0.8 g) in a worst case scenario was evaluated. High temperature was efficient in reducing the risk of pathogens; however, the temperature distribution in the unit is not sufficient to reduce pathogens. Therefore, to efficiently reduce pathogens during the post-treatment, the unit requires an insulator to maintain the temperature.

INTRODUCTION

Compost of human faeces used as fertilizer can be harmless and useful because it becomes part of nutrient recovery. A pilot model of a composting toilet was installed in a rural region of Burkina Faso to perform a source recycling system which makes compost from human faeces. Initial experiments were performed on some samples taken from the composting toilet. Results showed that pathogens such as bacteria and parasites still remained in the compost after withdrawal from the rural model of composting toilet after three months of operation. Therefore, post-treatment of the collected compost is required to minimise the health risk when recycling the faeces as fertilizer on farmland. For the inactivation of pathogens, several methods of treatments are proposed, including heating, drying, chemical treatments, treatment by worms, long storages times, etc. In low income countries like Burkina Faso, people cannot pay consumptions for post-treatment, however, they have abundant solar energy. Therefore; this study proposes a solar disinfection unit to inactivate the pathogens. The operation conditions to inactivate pathogens should be designed based on the risk assessment by setting a safe level of pathogens concentration in the compost after post-treatment.

Norovirus and Ascaris eggs were selected for the reference pathogens in this study. Because, noroviruses are a major cause of human gastroenteritis, and they are frequently associated with food, water contamination [1] and accidental ingestion. On the other hand, Ascaris infections are very common in developing countries. One fertile egg can cause infection of Ascarisis to humans.

These enteric infections can be transmitted through the compost from faeces to the human body with pathogenic species. Quantitative microbial risk assessment (QMRA) has been widely used to establish the health risks associated with wastewater reuse in both developed and developing regions under different scenarios. The QMRA-Monte Carlo techniques (QMRA-MC) based on the work of Haas et al. [2] was used to estimate risk in this study.

The objectives of this study are to perform risk assessment for the design of the post-treatment unit by using the QMRA-MC techniques and to determine the treatment time to reach the safe level of pathogens in the compost.

MATERIAL AND METHODS

Post-treatment Unit

People would collect the compost from the rural model of composting toilet with urine diversion (Fig-
ure 1) in the pilot families and use in their gardens as fertilizer. Application of the post-treatment would be achieved by spreading the compost evenly on the steel box as shown in Figure 2. The box was fabricated with a length of 60 cm, a width of 40 cm, and a depth of 10 cm. The total volume of the box is 24L. The steel box has steel septa which facilitate deep penetration of heat to compost. The steel box is painted black in colour to aid in the absorption of heat. The steel box does not have a solar concentrator [3,4,5]. The temperature distribution of the compost in the box was measured at 3 positions which were 1 cm, 5 cm, and 10 cm from the surface.

**Scenarios for Reuse of Compost**

During the utilisation of the compost, people may accidentally ingest compost with the pathogens orally. The people exposed to the pathogens would have diseases with a probability estimated by risk assessment. We set 6 scenarios, the compost at constant temperatures (40°C, 50°C and 60°C, S-1 to S-3) and actual temperature at 3 positions (1 cm, 5 cm and 10 cm from the surface) in the steel box (S-4 to S-6) as a post-treatment for the assessment. For the calculation of concentration in the compost, the inactivation rate coefficient from our previous measurement was used [4,5]. The details of the ingestion model are as follows:

- To consider the worst case, 50,000 eggs/g in wet faeces is excreted from a heavily infested person [6]. The value of the initial concentration of *Ascaris* eggs was 336 eggs/g-dry compost. This number was estimated by multiplying the number of eggs excreted per gram (50,000) by the 100g of compost dividing by the bulk density of the compost (14881 g/cm³).
- Highly infested person of viral infection excretes a maximum of $10^{11}$ viral copies/g in faeces from highly infected person [1,7,8] was used for the risk assessment taking account of the highest risk. Assuming this concentration, the initial concentration was estimated at $6.72 \times 10^8$ viral copies/g-dry compost. This number was estimated by multiplying the number of norovirus excreted per gram ($10^{11}$ viral copies/cm³) by the 100 g of the compost and dividing by bulk density of the compost (14881 copies/cm³).
- Ingestion rate of compost is 150–800 mg/event. This is used in the risk assessment of dioxin in soil ingestion rate [9].
- Post-treatment would be done every four months.
- The concentration of pathogens in the compost after the post-treatment was estimated using the first-order kinetic model from our earlier studies on *Ascaris* eggs and indicator MS2 bacteriophage inactivation. The estimated number of days was assumed to be 9 days, 6 days and 3 days for 40°C, 50°C and 60°C respectively. The estimated inactivation rate coefficient values for 40°C, 50°C and 60°C were 0.22 h⁻¹, 0.92 h⁻¹ and 1.22 h⁻¹ respectively, for *Ascaris* eggs and MS2 $k$ values were 0.25 h⁻¹, 0.45 h⁻¹ and 0.80 h⁻¹[4,5].
- The moisture content of all treatments was 50%.

![Figure 1. Arrangement of composting toilet.](image-url)
Hazard identification—Farmers performing post-treatment would be exposed to pathogens in the compost. There are several groups of pathogens, but the pathogens of considerable interest in the study area are *Ascaris* eggs and viral infections (norovirus) because *Ascaris* and norovirus are also known to be the most resistant to treatment processes [10,11]. Accidental ingestion of a small dose consequently implies a high risk of infection compared to many other pathogens [9].

Dose-response assessment—The QMRA-MC was used to estimate risks of *Ascaris* and norovirus infection. The study by Navarro *et al.* found that *Ascaris* infection data best fitted the β-Poisson dose-response equation [12]:

\[
P_I(d) = 1 - [1 + (d / N_{50})(2^{1/\alpha} - 1)]^{-\alpha} \tag{1}
\]

where \(P_I(d)\) is the probability of infection in an individual (infection/event), \(d\) is the ingested number of *Ascaris* eggs on one occasion (eggs/event), \(N_{50}\) is the mean infective dose number of *Ascaris* eggs (eggs), \(I\) means considerable spice for calculation of probability (–) and \(\alpha\) is an infectivity constant of *Ascaris* (–). They found the values of \(N_{50}\) and \(\alpha\) to be 859 and 0.104, respectively. Since they were working with epidemiological data on *Ascaris* prevalence rather than conducting human *Ascaris* dose-challenge studies, the value found for \(N_{50}\) is not a measure of the actual median *Ascaris* infective dose, but rather an empirical value arising from their statistical analyses [13].

The annual probability of infection, \(P_{I(A)}(d)\) (pppy), is given by:

\[
P_{I(A)}(d) = 1 - [(1 - P_I(d))^n] \tag{2}
\]

Where \(n\) is number of events per year to the single *Ascaris* dose (–) [13]. For norovirus, the dose response data set of Teunis *et al.* [1] was used in place of the β-Poisson equation [13].

Exposure assessment—The human exposure assumed to take place is an event when farmers work on compost. Practically, one egg is enough to cause an infection. Norovirus has an extremely low infectious dose [8].

Risk characterisation—The Monte Carlo technique has been used to evaluate the infection risk. The random number is applied for estimation of variables with distributions for simulation of Equations (1) and (2).
The simulation was repeated 10,000 times [13]. Then, 95 percentile of the probability was estimated as the infection risk.

**Temperature Distribution**

Considering actual practices, solarisation is one of the main processes for disinfection of enteric pathogens, because sunlight is available in the study region. The solarisation relates to the ambient temperature, while the temperature is not constant as shown in Figure 3. A two day diurnal average ambient temperature was measured during April 2014 in the post-treatment unit. April is one of the hottest months during the year in the study region. From the temperature profile, it was assumed that temperature remains constant during the night and continually increases during the day.

**RESULTS AND DISCUSSION**

The change in concentration of *Ascaris* under S1 to S3 is shown in Figure 4. The concentration declined
from the initial value of 336 eggs/g-dry compost. High temperature gives high decline rate of the concentration due to high inactivation rate coefficient. Figure 5 illustrates the decrease concentration of *Ascaris* eggs with time under S4 to S6. High and low reduction rates are found in the figures. This is because high temperature at day time and low temperature in night respectively give high and low reduction. All conditions obtained 6 log reduction of eggs in 60 hours and the difference of the position in the steel box gave slight difference of the concentrations. The change in concentration of norovirus with elapse of time under S1 to S3 are shown in Figure 6. The concentration declined from the initial of $6.72 \times 10^8$ copies/g-dry compost. Higher temperature condition also gives higher decline rate. The time course of concentrations under scenarios S4 to S6 is represented in Figure 7. The reduction rate of norovirus concentration had slight difference among three
scenarios like *Ascaris* case and was lower than 40°C, however, S4 to S6 have higher temperature period than 40°C. This might be result of much effect of low temperature less than 40°C, especially at night.

The 95-percentile annual risk of *Ascaris* and norovirus infections for the scenarios from their concentration in the compost as shown in Figures 8–11. The risk of the both pathogens are almost 1 at the initial for all scenario. This means the people who uses the compost would be heavily polluted by the pathogens. They would be infected if the composting reactor fails to reduce the pathogen concentration and also if they do not apply the post-treatment. Schönning *et al.* [14] also reported a 95-percentile risk of rotavirus and *Ascaris* for 0 months’ storage in a worst case as 1. After the post-treatment, the risks for the *Ascaris* under S1 to S3 were reduced and reached a safe level at 48 h, 21 h and 10 h for 40°C, 50°C and 60°C, respectively. Under the steel box, the required times to reach the safe level were respectively 51.5 h, 54 h and 54.5 h for S4 to S6. This was same level of S1 while the temperature distributions in the steel box would give longer time.

Figure 7. Change in norovirus concentration in the steel box.

Figure 8. *Ascaris* annual infection risk associated with post-treatment at: 40°C, 50°C and 60°C where the line indicates the safe level.
to reduce the concentration of pathogens from estimation from maximum temperature. During the day, there is sufficient increase in temperature but it suddenly decreases towards the evening and in the nights. This phenomena causes sufficient inactivation by the balance of the high inactivation rate at high temperature and the low inactivation at low temperature. To reduce treatment time, we need to improve the post-treatment unit by increasing the maximum temperature and keeping temperature during the night. The required times to the safe level for norovirus under constant temperatures were 139 h, 62 h and 28 h for 40°C, 50°C and 60°C, respectively. The time required to reach the safe level in the steel box at the bottom, middle and
top were respectively 147 h, 161.5 h and 170 h. These are longer than 40°C case, therefore, the treatment unit should be improved. Comparing *Ascaris* and norovirus, norovirus requires more time than *Ascaris* to reach safe level of $10^{-4}$ pppy [15]. Therefore, norovirus is more important indicator for the design of the unit, even *Ascaris* eggs have possibility to survive several months in a soil system [16].

Risk assessments for post-treatment of compost have received very little documentation. Seidu et al. [16] reported increased levels of *Ascaris* and rotavirus infection for farmers due to accidental ingestion of contaminated soils. The estimated median risk values for farmers were 0.99 and $7.2 \times 10^{-2}$ pppy for Ascariasis and rotavirus. The study indicated that the elevated hazard posed by the soils on the farm could be attributed to the persistence of *Ascaris* in the soils. This implies that compost must be treated properly before reuse as fertilizer so as not to pose even greater risk in the soils. However, in semi-arid regions where the compost is expected to be used, inactivation of *Ascaris* occurs in soils rapidly [8] which indicates that post-treatment in these regions could be feasible. The results of our study indicate that high temperature with prolonged treatment time could reduce the hazard considerably.

Mara and Sleigh [13] reported risk of fieldworkers’ involuntary ingestion of 1–10 mg of waste-water contaminated soils. The median of norovirus infection risk for an ingestion of 100–1000 mg, 10–100 mg, 1–10 mg of contaminated soil were 0.98, 0.32, and $3.7 \times 10^{-2}$ pppy respectively. The study also reported the median *Ascaris* infection risk for ingestion of 100–1000 mg, 10–100 mg, 1–10 mg of contaminated soils as 0.14, 1.5 $\times 10^{-2}$, and $1.5 \times 10^{-3}$ pppy respectively. In this study, the risk associated with the exposure of norovirus was estimated to be the highest, thus, this level of pathogen reduction will provide sufficient protection against bacterial and protozoa infections.

**Conclusions**

Higher temperature is efficient for reducing risk of pathogens. Temperature distribution in the steel box is not sufficient to reduce pathogens. Therefore, to efficiently reduce pathogens during post-treatment the steel box needs an insulator to maintain temperature. Guidelines for the design of the post-treatment facility are as follows:

- For norovirus, under S1 to S3, post-treatment requires approximately 140 h, 60 h, and 30 h for 40°C, 50°C, and 60°C respectively to achieve the safe level of $10^{-4}$ pppy. For *Ascaris*, post-treatment requires approximately 50 h, 24 h, and 12 h for 40°C, 50°C, and 60°C respectively.
- For S4-S6, norovirus requires 147 h, 161.5 h, and 170 h for the S4, S5 and S6 of the steel box respec-
tively to reach a safe level and Ascaris requires 51.5 h, 54 h, and 54.5 h for the bottom, middle and top of the metal box respectively.

Farmers should be educated on high risks associated with compost and how to be safe during post-treatment. Effective post-treatment could reduce risk of pathogens in compost from the composting toilet and may provide a cheaper alternative to fertilizer for rural household farmers. To reduce health risk from pathogens in rural communities it is important to create affordable methods for post-treatment.

REFERENCES