GLOBAL WATER PATHOGEN PROJECT
PART FIVE. CASE STUDIES

CAN FARMERS IN BOLIVA SAFELY IRRIGATE NON-EDIBLE CROPS WITH TREATED WASTEWATER?

Erin Symonds

University of South Florida
St. Petersburg, United States

Matthew Verbyla

San Diego State University
San Diego, United States

James Mihelcic

University of South Florida
Tampa, United States

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Summary

Highlights

- Exemplifies how to safely farm with treated wastewater in a rural setting
 - Necessary precautions can be identified from limited virus data, which can differ from faecal indicator bacteria
 - Safe wastewater reuse in agriculture addresses SDG targets 2.3, 2.4, 3.2, 3.3, and 6.3
 - Distinct approaches needed for adults and children to ensure safe reuse on the farm
- A multibarrier approach is necessary to ensure safe wastewater reuse in the fields

Graphical abstract

Summary

Risk Management Objective

This case study aimed to determine if farmers, in low income countries, can safely reuse treated wastewater from an existing waste stabilization pond (WSP) system for irrigation, or are additional control measures or treatment processes required to reduce exposure to viral pathogens and meet a specified health target?

Location and Setting

The study took place in a town, located in a culturally diverse region of the Caranavi province of Bolivia near the Alto Beni River, an important inland fishery system in the Amazon River basin. The local economy is driven by citrus fruit production for domestic sale and cacao beans for factories that manufacture chocolate. Many farmers chew coca leaves while working, resulting in frequent hand-to-mouth contact. Reclaimed wastewater can provide a local source of irrigation water that contains valuable nutrients and may be less carbon intensive than other sources. Like many areas of the world, most population growth will occur in small cities, such as the one studied here, that are closely linked to agricultural zones.

Figure 1. Community-operated waste stabilization pond (WSP) system with (a) a facultative pond and (b-c) two maturation ponds in series (left); case study site location (right; photo by M.E. Verbyla).

Description of the System

The wastewater treatment system serves 780 people and consists of flush toilets, a gravity-driven conveyance network, and three WSP in series. While it provided high removal of faecal coliforms, limited virus removal was measured. Treated effluent is discharged to a nearby surface water, but some farmers would like to use the effluent for irrigation. This sanitation system is managed and operated by a volunteer community water committee.

Outcome and Recommendations

Minor additional control measures are needed to reduce the risk of virus exposure during farming and meet the specified health target for this study. It is better to use at least two of these measures in combination to create "multiple barriers" for pathogen control. If one barrier fails, others will still provide some protection.

Additional Treatment. The hydraulic performance of the ponds could be improved by installing baffles and/or regular desludging of accumulated solids in the first pond. Also, the treated effluent can be stored in shallow, on-farm ponds prior to irrigation, where it will receive additional treatment.

Restrictive Measures. Children should not be allowed to play in irrigated fields.

Personal Protective Equipment. Farmers should use gloves to handle tools and equipment, and remove them to handle food or coca leaves. They should also have access to hand washing facilities.

Introduction

Wastewater use in agriculture facilitates water and nutrient recovery, offsetting energy needs for food production and reducing the degradation of aquatic ecosystems (Hamilton et al., 2007). Currently, 20 million hectares of land are irrigated with wastewater (Raschid-Sally and Jayakody, 2008). The extent of wastewater irrigation will likely increase in the future because of water scarcity, population growth, and the adoption of the Sustainable Development Goals (SDGs), which include a target to increase water recycling and safe reuse globally. Reclaiming treated wastewater is also beneficial because it applies nitrogen and phosphorus to land instead of surface water, which reduces the eutrophication potential of the sanitation system. Reusing treated wastewater may also lower the carbon footprint and embodied energy of sanitation systems, especially systems with high material and energy inputs (Cornejo et al., 2013). The World Health Organization (WHO) recommends a systematic risk-based approach to assess wastewater reuse via Sanitation Safety Planning (SSP; WHO, 2016), with a maximum health burden of 10-6 disability-adjusted life years (DALYs) lost per person per year. Since it has been suggested that 10-4 DALYs may be a more appropriate initial target for regions with high diarrheal disease burdens (Mara et al., 2010), the target of 10-4 DALYs was selected to evaluate the risk of reusing water from a three-pond waste stabilization pond (WSP) system in Bolivia.

While there are many ways to reduce pathogen concentrations in wastewater prior to reuse, WSPs are extremely prevalent worldwide and facilitate natural disinfection and removal processes without requiring high energy or material inputs (Kumar and Asolekar, 2016; Maynard et al., 1999; Oakley, 2005; Verbyla and Mihelcic, 2015; Verbyla et al., 2013a). Pathogen reduction is primarily achieved in tertiary maturation or polishing ponds. Based on Verbyla et al., 2013a), this system provided an average 3.4-log₁₀ removal of faecal coliforms. Since enteric viruses are often more resistant to treatment, enteric virus reference pathogens were directly measured. This case study highlights a quantitative microbial risk assessment (QMRA) of agricultural irrigation with treated effluent from a community-managed wastewater treatment system in Bolivia consisting of three WSPs in series (Figure 1; Symonds et al., 2014). The QMRA determines the additional log₁₀ enteric virus reductions required to safely reuse the treated effluent and considers the health risks to adult farmers as well as children at play in irrigation fields. The setting is like many areas of the world, where most population growth will occur in small cities closely linked to agricultural zones (Verbyla et al., 2013a).

Problem Formulation

The purpose of the QMRA was to determine the additional log₁₀ enteric virus reductions necessary to ensure the safe reuse of effluent from a three-pond community-managed wastewater treatment systems for irrigation. The work is based on a previously published study (Symonds et al., 2014).

The scope was defined by:

Hazard identification: Enteric viruses, represented by norovirus (measured by RT-qPCR) for adult farmers and rotavirus (measured by RT-qPCR) for children <5 years.

Exposure pathways: two exposure pathways were considered:

1. Accidental ingestion of irrigation water by farmers working and
2. Accidental ingestion of soil by children playing in fields irrigated with treated effluent.

Health outcome: DALYs lost per person per year was selected as the health outcome, with a target of 10-4 DALYs per person, since Bolivia has a high diarrheal disease burden (Mara et al., 2010).

Exposure Assessment

Source: The concentrations of norovirus and rotavirus were determined by molecular methods (RT-qPCR) from composite samples of treated wastewater collected over a 24-hour period in June 2012. Since this study used molecular methods to determine rotavirus concentrations and culture-based methods were used to develop the dose-

response relationship (Ward et al. 1986), it was necessary to harmonize rotavirus concentrations using a ratio 1:1000 to 1:1900 gene copies to focus-forming units (Mok and Hamilton, 2014). Such an adjustment was not needed for norovirus due to congruent methods used in this study and in the dose-response studies.

Barriers/controls: The risk of enteric virus illness from wastewater reuse for a three-pond wastewater treatment system was executed with respect to farmers and children playing in fields irrigated with treated effluent (Symonds et al., 2014).

Exposure : The assumed amount of virus ingested during exposure to treated wastewater effluent was determined based upon the assumed volume of effluent ingested and the concentration of enteric viruses in the effluent. It was assumed that adult famers and children playing in fields ingested the equivalent of 1.0 mL of wastewater effluent per day (Ottoson and Stenström, 2003), during 75 days/year for farmers and 150 days/year for children (Mara et al., 2007; Seidu et al., 2008). Log-normal distributions of virus concentrations were assumed, based on those measured in the treated wastewater effluents (Table 1).

Table 1. The distributions of norovirus and rotavirus concentrations (copies/mL) used in the QMRA assessment to determine if the effluent from the wastewater treatment pond system could be safely reused for restricted agricultural irrigation.

Population At Risk	Reference Enteric Virus	Assumed Distributions of Reference Enteric Virus Concentrations (copies/mL) In Treated Effluent
Adult farmers	Norovirus	lognormal (mean=363, sd=1.86)
Children <5 years at play	Rotavirus	lognormal (mean=1622, sd=3.55)

Health Effects Assessment

Dose-response models were used to determine the additional virus removal necessary to safely reuse of the wastewater treatment system effluent with respect to farmers and children in fields. The hypergeometric model (Teunis et al., 2008) with a Pfaff transformation (Barker et al., 2013; Mok et al., 2014) was used for norovirus, where the probability of infection was calculated as:

$$P_{infNV} = 1 - (2F_1(\beta_{NV}, \frac{C_{NV}V(1-a_{NV})}{a_{NV}}, \alpha_{NV} - \beta_{NV}; a_{NV}) (\frac{1}{1-a_{NV}})^{\frac{-(C_{NV}V(1-a_{NV}))}{a_{NV}}})$$

where $\alpha_{NV}=0.04$; $\beta_{NV}=0.055$; $a_{NV}=0.9997$ (Teunis et al., 2008); and where c_{NV} is the concentration of norovirus and V is the volume of water ingested. Not everyone who becomes infected develops an illness (there is the possibility that some become 'silent carriers'); therefore, a conditional probability of norovirus illness (the proportion of infected individuals developing symptoms of an illness) was calculated using:

$$P_{illinfNV} = 1 - (1 - \eta_{NV}c_{NV}V)^{-r_{NV}}$$

$$\text{where } \eta_{NV} = 0.00255; r_{NV} = 0.086 \quad (2)$$

Rotavirus probability of infection was calculated using the exact beta-Poisson model (Teunis and Havelaar, 2000):

$$p_{infRV} = 1 - {}_1F_1(\alpha_{RV}, \alpha_{RV} + \beta_{RV}, -c_{RV}V)$$

$$\text{where } \alpha_{RV} = 0.167; \beta_{RV} = 0.191 \quad (3)$$

and the conditional probability of rotavirus illness given infection was determined assuming a simple ratio of 0.9 (Havelaar and Melse, 2003):

$$P_{illinfRV} = p_{infRV} \cdot 0.9 \quad (4)$$

The probability of contracting an illness that would cause some type of disease burden was calculated as:

$$P_{ill} = P_{inf} \cdot P_{illinf} \quad (5)$$

To normalize the probability of illness per year for the two groups exposed for a different number of days per year, the following equation was used, where n is the number of days per year of exposure:

$$P_{illannual} = 1 - (1 - P_{illdaily})^n \quad (6)$$

Risk Characterization

Annual risks were expressed in terms of DALYs, assuming uniformly-distributed ranges for the average disease burden per case of illness from norovirus (3.71×10^{-4} to 6.23×10^{-3} DALYs per case; Mok et al., 2014) and rotavirus (1.50×10^{-2} to 2.60×10^{-2} DALYs per case; Havelaar and Melse, 2003; Prüss-Üstün et al., 2008), using the following equation:

$$DB = p_{ill_{annual}} \cdot B \quad (7)$$

For norovirus, it was assumed that a fraction of the population may have genetic resistance to infection; for this study, this fraction was assumed to be uniformly distributed from 0 to 0.2 (Mok et al., 2014). Risk of rotavirus infection was only calculated for children under the age of five and took into account the effect of vaccination programs by multiplying the disease burden (DB) by the fraction of children with susceptibility (due to the fact that they have not received the vaccine or the vaccine may have not been effective), calculated as:

$$S_f = 1 - e \cdot p_v \quad (8)$$

where:

p_v = 78% vaccinated WHO, 2014; e = efficacy ~ uniform (0.54, 0.79); Patel et al. 2013

QMRA was used to determine the additional $\log_{10}$ enteric virus reductions necessary to ensure a disease burden of $<10^{-4}$ DALYs per person per year, which has been considered a more appropriate target for regions with high diarrheal disease burdens (Mara et al., 2010), for both adult farmers working and for children playing in wastewater-irrigated fields. To incorporate uncertainty and variability, a Monte Carlo simulation with 10,000 iterations was implemented, using the distributional assumptions described above. Then, descriptive statistics (mean, median, percentiles) of the estimated $\log_{10}$ reduction values (LRV) required to achieve the health target of 10^{-4} DALYs were determined. The effluent required additional enteric virus reductions to ensure safe reuse for restricted irrigation (Figure 2). The median additional treatment required if children are exposed was 4.0- $\log_{10}$ units; therefore, it is not recommended that children have access to fields where effluent is used for irrigation. The median additional treatment required to protect adult farmers was approximately 0.9- $\log_{10}$ unit.

Figure 2. The additional virus concentration $\log_{10}$ reduction required for safe wastewater reuse in agriculture with respect to farmers (norovirus infection) and children at play in fields (rotavirus infection; adapted from Symonds et al., 2014).

It is important to consider the local context of exposure when completing QMRAs, especially when locally-derived exposure data is not available. This can be done using a sensitivity analysis. For this study, it was assumed that farmers accidentally ingest 1.0 mL of irrigation water per day while working. However, this assumption came from a publication written within the context of irrigation practices in Sweden (Ottoson and Stenström, 2003). In Bolivia, some farmers chew coca leaves while working, a practice that implies frequent hand-to-mouth contact and creates the possibility that greater volumes of irrigation water and/or soil are accidentally ingested. A sensitivity analysis revealed that if the amount of water accidentally ingested were doubled (increased from 1.0 mL to 2.0 mL per day), an additional virus reduction of 0.3-log₁₀ units (in addition to the log₁₀ reductions presented in Figure 2) would be required.

Risk Management

The reuse of the effluent from both wastewater treatment systems for restricted agricultural irrigation exceeded the health benchmark of 10⁻⁴ DALYs for adult farmers and children. Based upon a conservative interpretation of the QMRA (the upper 97.5% confidence interval), an additional 5.2-log₁₀ rotavirus reduction would be required to ensure the safety of young children playing in irrigation fields. To ensure the safety of farmers irrigating with treated effluent, up to 1.6-log₁₀ of additional norovirus reduction would be required.

Therefore, the following interventions are recommended:

- Children should not be allowed to play in fields irrigated with treated effluent from the wastewater treatment system described in this case study
- To protect farmers, additional treatment of the WSP effluent is recommended, as well as the use of personal protective equipment and practices.

The additional required reduction of norovirus risk can be achieved by adding an additional treatment unit to the end of the system or at the point of reuse. For example, an additional pond or constructed wetland cell with 50 cm depth and a hydraulic retention time of 10 days should achieve approximately 1-log₁₀ reduction (Silverman et al., 2014; Silverman et al., 2015). Alternatively, a sand filter followed by a UV disinfection [MEV1] lamp could be used (see Chapters on Disinfection). The installation of baffles on the two maturation ponds may prevent short-circuiting, which has been shown to reduce pathogen removal efficiency in WSP systems (Verbyla et al., 2013b). Exposure can be reduced by implementing practices that limit farmers' exposure to the water while working on the farm (e.g., personal protective equipment; subsurface irrigation; mechanization of farming activities; WHO, 2016). Although the enteric virus removal observed for this WSP system was slightly lower than those previously reported for similar-sized systems, the virus removal performance observed herein may have been impacted by the lack of maintenance (Symonds et al., 2014). Increased investments in the

maintenance of the system (e.g., removal of floating algae on the pond surfaces; Verbyla and Mihelcic, 2015) as well as increased stakeholder participation (Verbyla et al., 2015) may help to provide more efficient pathogen removal and ensure safe wastewater reuse.

Evaluation of the QMRA

The QMRA executed in this study provided a framework to assess that additional log₁₀ enteric virus reductions necessary to ensure the safe reuse of WSP effluent with respect to adult farmers and children at play in the irrigation fields. The additional virus reductions required could be easily achieved through a combination of additional tertiary treatment of effluents and the use of personal protective equipment by farmers. Although this model used actual virus measurements from the field together with dose-response curves for the health assessment, the results are limited by the model assumptions. While uncertainty and variability of virus concentrations were considered by using distributional assumptions for virus concentrations, the distribution parameters were estimated based on virus concentrations measured from only two composite sampling events in June 2012. If an outbreak of any of the reference pathogens were to occur, the amount of virus removal necessary for safe reuse may be much greater (Barker et al., 2013). For many community-managed wastewater treatment systems, the regular monitoring of pathogens (and even faecal indicators) may not be practical due to training required for community operators, the cost of the service and the lack of laboratories capable of providing it. Thus, there is a need for alternative indicators of microbial risk. In the present case study, we had the opportunity to quantify the concentrations of norovirus and rotavirus in the wastewater. A semi-quantitative approach, such as the one presented in the WHO's SSP guidelines (WHO, 2016), can be guided by quantitative information about pathogen concentrations and exposure (such as the information presented in Part Three of GWPP about pathogen concentrations in raw sewage, feces, and sludge, as well as the information presented in the GWPP Sanitation Technologies chapters about the removal of pathogens in sanitation systems using different technologies). The approach presented in this case study, together with reference values from GWPP, can be used to assess risk for wastewater reuse systems like the one presented here, in data-scarce and/or resource-limited regions. Professional judgement and knowledge of local practices (e.g. coca leaf chewing by farmers in Bolivia) are essential to appropriately assess risk and make subsequent management decisions in different contexts.

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reuse for two wastewater treatment pond systems in Bolivia. Water Research. 65: 257-270.

expressed here are those of the authors and do not necessarily reflect the views of the US NSF.

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The full paper can be found here: Symonds et al. 2014

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