



Pathogens and fecal indicators in waste stabilization pond systems with direct reuse for irrigation: Fate and transport in water, soil and crops



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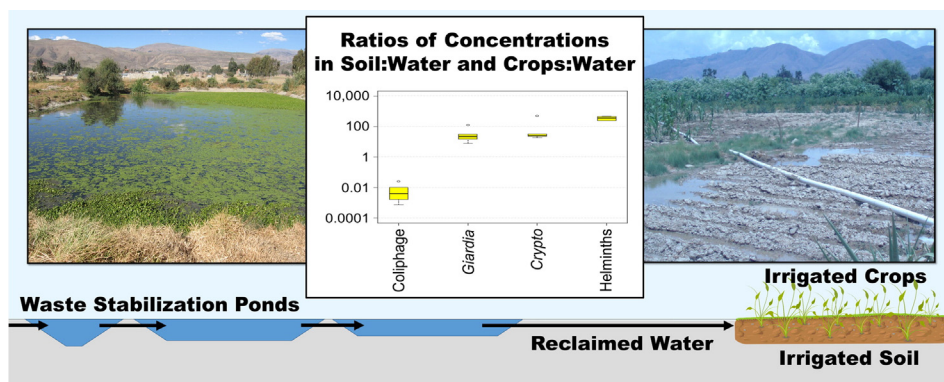
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HIGHLIGHTS

- Study of health risks from reclaimed wastewater irrigation from aging pond systems
- Coliphages, protozoan parasites, and helminths were measured in water/soil/crops.
- Sludge accumulation in ponds may limit removal of helminths more than *E. coli*.
- Ratios of microbes on crops/water highest for helminths > protozoans > coliphage
- Sludge evacuation and parasite removal in ponds are essential for safe water reuse.

GRAPHICAL ABSTRACT



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ABSTRACT

Wastewater use for irrigation is expanding globally, and information about the fate and transport of pathogens in wastewater systems is needed to complete microbial risk assessments and develop policies to protect public health. The lack of maintenance for wastewater treatment facilities in low-income areas and developing countries results in sludge accumulation and compromised performance over time, creating uncertainty about the contamination of soil and crops. The fate and transport of pathogens and fecal indicators was evaluated in waste stabilization ponds with direct reuse for irrigation, using two systems in Bolivia as case studies. Results were compared with models from the literature that have been recommended for design. The removal of *Escherichia coli* in both systems was adequately predicted by a previously-published dispersed flow model, despite more than 10 years of sludge accumulation. However, a design equation for helminth egg removal overestimated the observed removal, suggesting that this equation may not be appropriate for systems with accumulated sludge. To assess the contamination of soil and crops, ratios were calculated of the pathogen and fecal indicator concentrations in soil or on crops to their respective concentrations in irrigation water (termed soil-water and crop-water ratios). Ratios were similar within each group of microorganisms but differed between microorganism groups, and were generally below 0.1 mL g^{-1} for coliphage, between 1 and 100 mL g^{-1} for *Giardia* and *Cryptosporidium*, and between 100 and 1000 mL g^{-1} for helminth eggs. This information can be used for microbial risk assessments to develop safe water reuse policies in support of the United Nations' 2030 Sustainable Development Agenda.

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1. Introduction

Waste stabilization ponds (WSPs) are frequently used for wastewater treatment in small cities, towns, and regions with large areas of land but limited financial capital, partly because they are resilient systems that perform well and remove pathogens with limited maintenance requirements (Mara, 2003). However, not all of these systems are well-maintained throughout their life cycles. The removal of sludge from primary WSPs is a capital maintenance expenditure required every 2 to 15 years (depending on the system design and solids loading rate). In low-income communities with WSP systems, the amortized cost of sludge removal is often not included in the annual operation and maintenance budget, creating a major sustainability issue (Oakley et al., 2012). The performance of WSP systems is affected by sludge accumulation (Verbyla et al., 2013a). Accordingly, it is necessary to understand the removal of pathogens for WSPs in which sludge has accumulated for years without removal.

The treated water from WSP systems is often used for irrigation. Although the social, economic, and environmental benefits of wastewater reuse have been well-documented (Cornejo et al., 2013; Mo and Zhang, 2012), a large portion of wastewater use for irrigation occurs in low-income regions where wastewater treatment systems are overloaded, not well-maintained, or abandoned altogether. For example, nearly 2.4 billion m³ of treated wastewater are directly used for irrigation each year in North Africa and the Middle East (FAO, 2015), where many wastewater facilities are heavily overloaded (Ghneim, 2010; McIlwaine and Redwood, 2010). More land area in Latin America and the Caribbean is equipped for direct wastewater irrigation than in the Middle East and North Africa combined (FAO, 2015), but less than 10% of the wastewater in this region receives adequate treatment, partially because of the large number of treatment plants that are experiencing operational problems, malfunctioning due to the lack of maintenance, or abandoned (CREW, 2014; Libhaber and Orozco-Jaramillo, 2012). The removal of fecal indicators and parasites in WSPs has been previously characterized (Ayres et al., 1992; von Sperling, 2005); however, while these models take into account pond size and hydraulic retention time (HRT), they may not necessarily account for the malfunction concerns resulting from a lack of maintenance in older WSP systems. The absence of maintenance for wastewater treatment systems thus creates uncertainty about the risks associated with wastewater use practices throughout the world. This is alarming, given that Target 6.3 of the Sustainable Development Goals is to substantially increase water recycling and reuse globally by 2030 (United Nations, 2015).

Further complicating this issue is the fact that little is known about pathogen fate and transport in these under-maintained wastewater treatment and unregulated wastewater use systems. Data about pathogens in water, soil, and crops from wastewater irrigation operations in developing countries are often not available because few laboratories in these regions are equipped to measure pathogens in environmental samples. The 2006 World Health Organization (WHO) Guidelines (WHO, 2006) recommend the use of quantitative microbial risk assessment (QMRA) to develop safe water reuse policies. This requires measuring or assuming quantities of human pathogens in wastewater, and then assuming their fate and transport through treatment processes and into the irrigation fields and crops to which farmers and consumers are exposed. In previous QMRAs (e.g., Mok and Hamilton, 2014; Shuval et al., 1997) and in an example from the 2006 WHO Guidelines for unrestricted water reuse for irrigation (WHO, 2006), quantities of pathogens on irrigated crops have been estimated by multiplying their concentration in water by the volume of water retained by a crop after irrigation. This approach may be flawed, since not all pathogens in this water necessarily remain on the crop, and some pathogens may remain from previous irrigation events. Concentrations of pathogens and fecal indicator organisms in irrigation water are seldom compared with their respective concentrations in irrigated soil and on irrigated crops.

The objective of this study was to assess the fate and concentrations of a broad range of human pathogens and fecal indicator organisms in water samples from WSP systems serving small cities (<500,000 residents) and in soil and crop samples from fields irrigated with the effluent of those systems. The organisms chosen for this study were *Escherichia coli*, coliphage, *Giardia*, *Cryptosporidium*, and helminth eggs. The Cochabamba Valley was selected due to the fact that it was identified as the most representative region for wastewater use practices in Bolivia (GIZ, 2011); wastewater is used to irrigate more than 5700 ha of crops in this valley alone (Ministerio de Medio Ambiente y Agua, 2013). WSPs were chosen as the technology because they are among the most common wastewater treatment technologies used globally (Verbyla, 2015), especially when wastewater is used for irrigation. Results from a survey of 111 wastewater treatment systems in regions of Bolivia with water deficits revealed that approximately half of the systems were WSPs (Ministerio de Medio Ambiente y Agua, 2013). After a preliminary survey of eight wastewater treatment plants in the Cochabamba Valley, two WSP systems serving the towns of Arani and Punata were selected as case examples for the study. These systems were selected because they both served small cities, had similar layouts, and had been in operation for at least 10 years. Also, farmers applied 100% of the effluent from both systems directly to fields during the dry season (which made sample collection feasible at different times throughout the year). The wastewater treatment plants in Arani and Punata are officially managed by municipal wastewater companies, but in practice they have not been well maintained and were largely abandoned at the time of the study. Sludge had not been removed from ponds in either system. This is common throughout Bolivia, where 37% of wastewater treatment systems are not functioning and many other systems perform poorly because of maintenance problems (Ministerio de Medio Ambiente y Agua, 2013); it is also common throughout the developing world (CREW, 2014; Libhaber and Orozco-Jaramillo, 2012; Patiño Gómez and Lara-Borrero, 2012). Because these WSP systems were under-maintained, it was hypothesized that the removal of the selected pathogens and fecal indicator organisms would be lower than rates previously reported (Ayres et al., 1992; von Sperling, 2005), leading to potentially higher densities in irrigated soil and on crops.

2. Material and methods

2.1. Waste stabilization pond and irrigation systems

The wastewater treatment systems in Arani and Punata use a combination of anaerobic, facultative, and maturation ponds, some in series, some in parallel (Fig. 1). The system in Arani, which received an average flow rate of approximately 750 m³/day, contained two 425 m³ anaerobic ponds (in parallel), followed by two 1500 m³ facultative ponds (in parallel), two 950 m³ primary maturation ponds (in parallel), and two 950 m³ secondary maturation ponds (in parallel). This system was constructed in 2000 and at the time of sampling, sludge had never been removed. The total theoretical HRT, based on the original pond volumes (not considering sludge accumulation) and the flow rate measured at the time of sampling, was 10 days. However, sludge had accumulated to the point where it blocked the entrance to many of the ponds, causing a situation where wastewater only flowed through one of each of the ponds in parallel. The sludge that had accumulated in the ponds receiving wastewater was estimated to occupy roughly 80% of the pond volumes. Also, wastewater was only flowing through one of each of the duplicate ponds in series, further reducing the effective volume by half. Considering the loss of volume due to sludge accumulation and uneven wastewater flow, the total theoretical HRT for this system at the time of sampling was probably closer to only one day (Iriarte et al., 2013; Mercado et al., 2013).

The WSP system in Punata received an average flow of 2730 m³/day, and consisted of three 1300 m³ anaerobic ponds (in parallel), followed

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