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QUANTITATIVE MICROBIAL RISK ASSESSMENT (QMRA) FOR DOMESTIC NON-POTABLE REUSE OF GREYWATER: A CASE STUDY FOR A BRAZILIAN HOUSEHOLD

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ABSTRACT

Reuse of greywater has been studied as an alternative for non-potable uses. The goal of this paper was to quantitatively assess the microbial risk from the reuse of greywater treated in a household case study. A Quantitative Microbial Risk Assessment was applied to evaluate the treated greywater. This approach was conducted by taking as reference the pathogens Rotavirus, *Campylobacter* and *Cryptosporidium*, the worst cases of water-borne diseases of the families of viruses, bacteria and protozoa, respectively, according to World Health Organization. The uses included in this study were garden irrigation and toilet flushing. The findings showed that toilet flushing exposure presented the highest microbial risk with a median value of the order of 2.7×10^{-5} DALY per person per year. Even though this is higher than the World Health Organization recommendation (10^{-6} DAL Ypppy), it was considered insignificant within other authors' classification and less hazardous compared to several other actions that cause the health inability in Brazilian population.

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INTRODUCTION

On-site reuse of Treated Greywater (TGW) for non-potable purposes has been gathering interest as an alternative source to centralized systems in water-stressed regions to reduce pressure on drinking water supplies (Schoen *et al.,* 2017; Schoen & Garland, 2015; Sharma *et al.,* 2013). Moreover, for highly urbanized regions on which residential water consumption might represent more than two thirds of total water demand (Gonçalves, 2006), decentralized sources could increase the level of sustainability in urban water systems as well as reduce effluent disposal (Larsen *et al.,* 2016; WWAP, 2017). Greywater (GW) is defined as the wastewater from showers, bathtubs, bathroom sinks, and washing machines, accounting for about 50 to 80% of waste water produced in a household (Christova-Boal *et al.,* 1996; Eriksson *et al.,* 2002). Many studies have confirmed its potential for reuse (Atanasova *et al.,* 2017; Fountoulakis *et al.,* 2016; Teh *et al.,* 2015), presenting a higher quality compared with municipal wastewater, with lower concentrations of nitrogen and organic matter. However, such water still contains microbial and chemical contaminants that can put the user's health at risk if ingested, inhaled, or absorbed through the skin (Li *et al.,* 2009; Edwards *et al.,* 2004; May, 2009). Kaercher *et al.* (2003), studying the population perceptions about GW reuse in Australia, asserted that while users recognized both reasons and benefits associated with GW recycling, there was no spontaneous desire to follow this practice. One of the major reasons for such discouragement was the potential health risks that this practice could yield (Po *et al.,* 2003; Nancarrow *et al.,* 2002; Hyde *et al.,* 2016). Assessing the suitability of non-potable water for human activities requires an estimate of the hazard associated with the user's health. The Quantitative Microbial Risk Assessment (QMRA) is a formal probabilistic

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methodology used to estimate the potential risk for human health under scenarios of exposure to microbial hazards (Haas *et al.,* 1999). QMRA has been applied for multiple water regulatory processes (U.S. EPA, 2014; WHO, 2016) and is the recommended method for the risk assessment on GW reuse (WHO, 2006). The objective of this study was to estimate the risk to human health associated with the reuse of GW for non-potable domestic purposes. A QMRA was conducted in a case study in a Brazilian household.

MATERIALS AND METHODS

Grey water treatment system

The GW treatment system was built in a high-income single-family household in the city of Feira de Santana-BA, Brazil, with two adults and two children under four years old. The system (Figure 1) treated the GW from the showers, washbasins and clothing washing machine in the residence studied and consists of a pretreatment stage (removal of coarse solids), a compartmentalized anaerobic reactor and an aerobic intermittent filter.

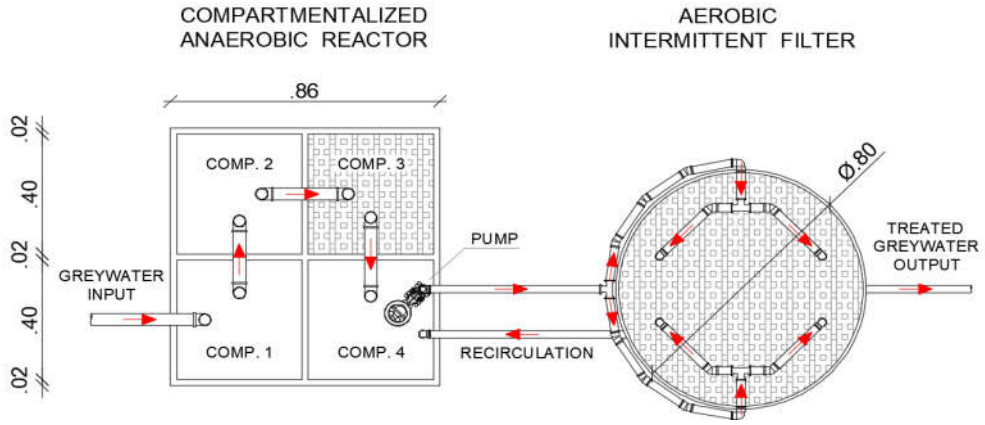

Figure 1.Greywater treatment system design (dimensions in meters)

Qrma model

According to the methodology proposed by Hass *et al.* (1999), the approach consists of four stages: (I) Hazard identification; (II) Exposure assessment; (III) Dose-response evaluation; and (IV) Risk characterization.

Hazard identification

For this study, human-infectious pathogens Rotavirus, *Campylobacter*, and *Cryptosporidium* were used as reference hazards for treated GW reuse assessment, following the guidelines proposed by WHO (2006), which represent the worst case considering the class of viruses, bacteria and protozoa (Ahmed *et al.,* 2005). To estimate the pathogen concentrations, a fecal indicator *Escherichia coli* (*E. coli*) was measured in the TGW.

Table 1. Data used to estimate [*E. coli*]:[Pathogen] ratios in greywater (Ahmed *et al.*, 2005)

Data	Ratio [*E. coli*]:[Pathogen]		
	Rotavirus	*Campylobacter*	*Cryptosporidium*
Median	10^5	10^5	10^6
Lognormal 5th percentile	10^4	10^4	10^5
Lognormal 95th percentile	10^6	10^6	10^7

We used a ratio between *E. coli.* and the infectious pathogens based on Ahmed *et al.* (2005), a method previously used by López-Pila *et al.* (2000) and Craig *et al.* (2003), which follows a lognormal distribution. The ratio between the fecal indicator and the reference hazard pathogens is shown in (Table 1).

Exposure assessment

The total volume of GW ingested for each domestic use was defined as well as the frequency of daily exposure. The selected uses in this study included garden irrigation and toilet flush water. We adopted a normal distribution for frequency of use of garden irrigation, with values for minimum, median and maximum of 0,3 and 7 per week. All the other frequency and exposure data were obtained from Ashbolt *et al.* (2005). According to the authors, the estimated frequency of toilet flushing follows a triangular distribution with values for minimum, median and maximum of 2, 4 and 6 per day. The estimated volumes of exposure to GW during both toilet flush and garden irrigation follow a triangular distribution with values for minimum, median and maximum of 0.01, 0.1 and 0.5 mL respectively.

A compilation of the data used for the exposure assessment is presented in Table 2.

Dose-response assessment

The daily probability of infection was calculated for each proposed use based on the methodology of Haas *et al.* (1999).The dose of pathogenic organisms for a single exposure was calculated by using Equation 1:

$$d = N \times V_{con} \times f \quad \text{.....(1)}$$

where:

d is the dose of pathogens ingested in one exposure (MPN·day^{-1});

N is the pathogen concentration in greywater (MPN·mL^{-1});
V_{con} is the volume consumed in one exposure (mL·day^{-1});

f is the daily frequency of use. The pathogen dose-response model is a mathematical characterization between the dose of pathogen administered and the risk of infection in the exposed population. The two most used mathematical models are: the exponential (Equation 2) and the Beta-Poisson (Equation 3).

The definition of the model used varies according to the chosen pathogen, always seeking the best fit. In this paper, the exponential model was used for the evaluation of Cryptosporidium, while the Beta-Poisson model was used for Rotavirus and Campylobacter. The parameters used for calculation are shown in Table 3.

$$P_{inf} = 1 - e^{-r.d} \quad \text{.....(2)}$$

$$P_{inf} = 1 - \left[1 + \frac{d}{N_{50}}\left(2^{\frac{1}{\alpha}} - 1\right)\right]^{-\alpha} \quad \text{.....(3)}$$

where:

P_{inf} is the probability of infection from a single exposure;
r is a parameter for the exponential model;
$N_{50}$is the microbial dose eliciting 50% infections in the exposed population;
α is a parameter for the Beta-poisson model.

K is the disease/infection ratio.

The results were also calculated in Disability Adjusted Life Years (DALY) by using the DALY losses per case of disease from Mara (2006) through Equation 6. DALY is a metric that estimates the time lost because of disability or death from a disease in comparison with a long life free of disease (Mara, 2006; WHO, 2016). The use of DALY is considered efficient because it can put into comparison any action that causes the inability to live normally due to health problems, whether an injury caused by an accident or an acquired illness.

$$P_{DALY} = C_{DALY} \times P_d \quad \text{.....(6)}$$

where:
P_{DALY} is the disease burden in DALY pppy;
C_{DALY} = DALY loss per case of disease.

Table 2. Exposure data

Data of exposure	Distribution	Minimum	Maximum	Median	Mode
Volume consumed (mL)					
Garden irrigation[(1)]	Triangular	0.01	0.5	-	0.1
Toilet flush[(1)]	Triangular	0.01	0.5	-	0.1
Frequency of use					
Garden irrigation[(1)] (#/week)	Normal	0[(3)]	7[(3)]	3[(3)]	-
Toilet flush[(2)] (#/day)	Normal	2	6	4	-

(1) Ashbolt *et al.* (2005)
(2) Estimated by the authors

Table 3. Pathogen dose-response parameters

Reference pathogen	Model	Parameters	Parameter values	Reference
Rotavirus	Beta-poisson	α	0.25	Teunis et al., 1996
		N_{50}	6.2	
Campylobacter	Beta-poisson	α	0.15	Teunis et al., 1996; Hass et al., 1999
		N_{50}	896	
Cryptosporidium	Exponential	r	0.004	Teunis et al., 1996

Table 4. DALY losses and disease/infection ratios of rotavirus, *Campylobacter* and *Cryptosporidium* (Mara, 2006)

Reference pathogen	DALY loss	Disease/infection ratio
Rotavirus (for developing countries)	0.026	0.05
Campylobacter	0.0046	0.7
Cryptosporidium	0.0013	0.3

Risk characterization

Using the results from the previous sections, the adverse health effects for a defined period were estimated. In this study, the probability of infection per person per year (pppy) caused by on-site reuse of TGW was calculated using Equation 4.

$$P_t = 1 - (1 - P_{inf})^t \quad \text{.....(4)}$$

where:

P_t is the probability of infection per person per year;
t is the number of exposures per year.

Assuming that being infected does not necessarily imply the development of illness, we adopted a disease/infection ratio from Mara (2006) (Table 4). The probability of disease per person per year was calculated using Equation 5.

$$P_d = K \times P_t \quad \text{.....(5)}$$

where:
P_d is probability of disease pppy;

Since, each pathogen presents a different value for DALY loss, according to its severity, the data used for the reference pathogens are shown in Table 4. To reduce uncertainty, input data were represented as probability distributions rather than points. A 10,000-iteration Monte Carlo model was simulated using @Risk software version 4.5 Educational Edition (Palisade Corporation 2002).

RESULTS AND DISCUSSION

The GW treatment system showed a removal efficiency of the *E. coli* bacteria by one order of magnitude (Table 5). The median risk of disease estimated for on-site TGW reuse is shown in terms of risk of disease pppy (Table 6) and DALY pppy (Table 7) for each reference use. Rotavirus was the reference pathogen with the greatest impact, accounting for more than 90% of the total DALY pppy for the assessed water uses. Disease burden for both uses was below the limit proposed by (WHO, 2006) for drinking water (10^{-6} DALY pppy), except for the toilet flush for Rotavirus (2.7×10^{-5} DALY pppy). The treatment system presented 88.06% efficiency in the removal of coli forms. To be in accordance

with the WHO guidelines for drinking water, it should reach a 99. 26% efficiency, thus the estimated average density of E. coli in the TGW would be lower than 1.1×10^{2} MPN per 100mL. Comparing the disease burdens found for the domestic uses with previous QMRA studies focusing on alternative waters reuse, it is possible to notice that they are inside range, with similar orders of magnitude, as it can be seen in Table 8.

benchmark risk proposed by WHO would be the most appropriate or even be too conservative, especially for developing countries (Mara, 2010). The WHO itself states that this goal may not be achievable or realistic in some locations and circumstances in the short-term, on which the overall burden of disease is high for multiple exposure routes (water, food, air, etc.).

Table 5. *E. coli* concentration in raw and treated greywater

Greywater	*E. coli*counts in MPN/100mL(1)		
	Minimum	Maximum	Median
Raw (input)	1.3×10^{2}	9.0×10^{5}	1.6×10^{4}
Treated (output)	2.0×10^{1}	2.3×10^{4}	1.8×10^{3}

(1) Most Probable Number per 100 mL

Table 6. Median disease risk per person per year for treated greywater reuse

Use	Reference pathogen			Total risk of diseasepppy
	Rotavirus	*Campylobacter*	*Cryptosporidium*	
Garden irrigation	1.1×10^{-4}	4.3×10^{-5}	4.4×10^{-7}	1.5×10^{-4}
Toilet flush	1.0×10^{-3}	4.2×10^{-4}	4.2×10^{-6}	1.4×10^{-3}

Table 7. Median DALY per person per year for treated greywater reuse

Use	DALY.pppa^{-1}			Total DALY pppy
	Rotavirus	*Campylobacter*	*Cryptosporidium*	
Garden irrigation	2.8×10^{-6}	2.0×10^{-7}	5.7×10^{-10}	3.0×10^{-6}
Toilet flush	2.7×10^{-5}	1.9×10^{-6}	5.5×10^{-9}	2.9×10^{-5}

Table 8. Disease burden of alternative water reuse

Reference	Median Probability of disease pppy	Median DALY pppy	Description
Fewtrellet al. (2008)	-	2.3×10^{-5}	*Salmonella* health impacts from grey water reuse for hose irrigation
Pasin (2013)	2.6×10^{-1}	$3.6\times10^{-3(1)}$	*E. coli* disease burden for untreated grey water reuse for irrigation
Vaz (2009)	4.5×10^{-5}	$1.2\times10^{-6(2)}$	Rotavirus disease burden associated with treated grey water reuse for toilet flush (estimated ingestion of 0.1 mL)
Cohim (2012)	-	6.2×10^{-7}	Rotavirus disease burden associated with treated grey water reuse for toilet flush

(1) Calculated by the authors using DALY loss per case of disease from Havelaar *et al*. (2004)
(2) Calculated by the authors

Table 9. Suggested definition of severity of consequences of hazards based on increase of endemic disease in the community (Westrell *et al.*, 2004)

Item	Definition
Catastrophic	Major increase in diarrhoeal disease >25% or >5% increase in more severe disease or large community outbreak (100 cases) or death
Major	Increase in more severe diseases (0.1-5%) or large increase in diarrhoeal disease (5-<25%)
Moderate	Increase in diarrhoeal disease (1-<5%)
Minor	Slight increase in diarrhoeal diseases (0.1-<1%)
Insignificant	No increase in disease incidence (<0.1%)

Results for disease burden of Rotavirus considering TGW reuse for toilet flush were considerably higher than Cohim (2012) findings of 6.2×10^{-7} DALY pppy, using the same reference hazards and on-site GW treatment. However, this fact can be explained by the difference in treatment effectiveness each case study yielded, since for this specific case pathogen removal. In addition, we were conservative on the values of ingested water during exposure. For toilet flushing, Cohim (2012) used a volume 10 times lower. Pasin (2013) considered that all *E. coli* in the GW was pathogenic, therefore the author's result is comparatively the highest. Fewtrell *et al.* (2008) studied the annual risk of Salmonellos is in the reuse of GW for hose irrigation. Their result is of the same order of magnitude of our findings. This does not necessarily mean that the health risk found in this paper would not be acceptable. Discussions have taken place on whether the

In such cases, setting this limit from water-borne exposure alone would not have a huge impact on the overall disease burden. Instead, more contextualized values could be established (WHO, 2011). Taking into consideration the total burden of disease of toilet flushing using TGW, which was estimated at 2.9×10^{-5} DALY pppy, it would offer lower risks for human health in Brazil than firearm assaults, transportation accidents and melee attacks, with values of 1.9×10^{-2}, 1.8×10^{-2} and 4.3×10^{-3} DALY pppy, respectively (Malta *et al*, 2017). Therefore, to evaluate the severity of consequences of GW reuse, we adopted the classification proposed by Westrell *et al.* (2004), based on the increase of endemic diseases in a population as shown in Table 9. Studies estimate that the number of episodes of diarrhea per child under 5-years-old per year in developing countries ranges from 3 to 5 (Vasquez *et al.,* 1999, Lima *et al.,* 2000, Moraes *et al.* 2003). Adopting a

median value of 4 episodes pppy in Brazil, the highest probability of becoming ill by TGW exposure (1.0×10^{-3}pppy) would represent an increase of only 0.026% in the rate of endemic diseases. Therefore, consequences of TGW reuse in Brazilian households could be considered insignificant.

Conclusion

In this paper, we conducted a QMRA study on TGW reuse for domestic purposes, considering Rotavirus, *Campylobacter* and *Cryptosporidium* as reference pathogens. Our results indicate Rotavirus as the main source of human health risks in TGW reuse and toilet flush as the use with greater risk (2.9×10^{-5} DALY pppy). Although this value is not in conformity with the WHO guidelines for drinking water, using TGW for toilet flush would only represent 0.026% of increase in disease cases for Brazilian communities, a hazard that would be classified as insignificant. The results of this study on GW reuse can be used as reference for the development of policies in Brazil due to the lack of regulation on this matter as well as to support a risk-based orientation for users.

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