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Quantitative Microbial Risk Assessment (QMRA) of Campylobacter for Roof-Harvested Rainwater Domestic Use †

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Abstract: The present study evaluated the microbiological risk for roof-harvested rainwater (RHRW), with Campylobacter as the pathogenic microorganism of reference, using a Quantitative Microbial Risk Assessment (QMRA). QMRA has been widely used as an alternative method for epidemiological assessment of human exposure to microorganisms that can cause diseases, through a four-step process: hazard identification, exposure assessment, dose–response assessment, and risk characterization. The results presented drinking as the water use with the highest median value for microbiological risk, with 3.4×10^{-4} disability-adjusted life years (DALYs) per person per year (pppy), and bathing, food washing, hose irrigation and toilet flushing with median values of 6.5×10^{-7}, 4.0×10^{-7}, 2.1×10^{-7} and 1.4×10^{-7} DALYs pppy, respectively. Therefore, drinking would be the only water use that would require preliminary treatment for its safe use, considering the acceptable risk standards set by the World Health Organization for drinking water. However, with the adoption of a sanitary barrier and a simple point-of-use treatment system, it was observed that drinking rainwater would have a median microbiological risk of 2×10^{-6} DALYs pppy, enough to meet the safety criteria considering developing countries.

Keywords: risk assessment; rainwater harvesting; drinking water

1. Introduction

Roof-harvested rainwater (RHRW) has been increasingly adopted as an alternative water supply for domestic uses, including drinking, especially in rural areas of developing countries [1,2]. In Brazil, for example, since 2003, more than 588,000 cisterns have been built in order to provide safe water for rural communities in the Northeast that do not have access to centralized water supply systems [3].

However, there is an ongoing debate regarding whether RHRW should be used as drinking water [4]. Some epidemiological studies suggest that consumption of untreated rainwater does not contribute to the incidence of disease in a community [5,6], while others have documented contamination in stored rainwater, posing a definitive public health risk if consumed without treatment [7–9].

The World Health Organization (WHO) has created drinking water guidelines to ensure the provision of high-quality water around the world [10]. In order to satisfy these limits, especially regarding microbiological contaminants, chlorine has been applied in rainwater cisterns as a disinfection method in Brazil, raising the concern about consumption of chlorination by-products in drinking water, which are associated with cancer in humans [11–15].

In this context, there is an increasing need to assess human health risks associated with RHRW exposure, especially in developing countries, where its use is becoming more widespread. The Quantitative Microbiological Risk Assessment (QMRA) approach applies risk assessment principles to estimate the effects of human exposure to infectious microorganisms in different scenarios [16], and has been used worldwide to establish guidelines and recommendations for water quality (WHO, 2011), with many studies focusing on rainwater [7,8,17].

This study aims to assess the human health risks from untreated RHRW domestic use through the QMRA method, and analyze the overall impact for the adoption of a sanitary barrier and a point-of-use device to improve rainwater quality in RHRW systems.

2. Methods

2.1. Literature Review

Data collection regarding pathogen concentration in RHRW was conducted by searching web-based databases and governmental agencies' websites for key words such as 'roof-harvested rainwater', 'pathogens', 'health', and 'risk'. The literature review did not have any geographical restrictions, although English-language papers were the major source of information.

2.2. Quantitative Microbial Risk Assessment (QMRA)

A QMRA framework was applied to assess the potential microbial health risks associated with the following proposed uses for RHRW: bathing, food washing, hose irrigation, toilet flushing and drinking. Where possible, input data have been represented as probability distributions rather than point-estimates in order to reduce uncertainty. A Monte Carlo sampling composed of 10,000 iterations was used for simulations using the software @Risk version 4.5 Professional edition (Palisade Corporation 2002).

Results for health impacts were quantified using disability-adjusted life years (DALYs). DALYs are a summary measure of a population's health, allowing comparison of effects across a wide range of health outcomes. The measure combines years of life lost (YLL) as a result of premature mortality, with years lived with a disability (YLD) standardized using severity weights with a range from 0 (perfect health) to 1 (dead) [18–21].

The QMRA addresses a quantitative approach through simulation techniques and scenario modeling, following a four-step process [16], divided into hazard identification and characterization, exposure assessment, dose–response evaluation, and risk characterization.

2.3. Hazard Identification

The main source of waterborne pathogens in RHRW in Brazil is likely to be from faecal droppings from birds and other animals with roof habits. Other possible routes from the catchment surface, according to Sanchez et al. [22], include deposits of dirt, lichens and mosses, fungus or fallen vegetable material from the surrounding trees.

From the literature review, the most commonly found microorganisms in stored RHRW are Campylobacter, Cryptosporidium, Salmonella, Giardia, Escherichia coli and Enterococcus, all major etiological agents of gastroenteritis worldwide [23–27].

Campylobacter ssp. is linked with zoonosis in birds and animals that inhabit or transit on the roofs [28,29], being one of the most important causes of acute gastroenteritis worldwide [10]. In addition, it has been isolated from rainwater supplies (Table 1) and implicated in illness from rainwater supplies used for drinking water [30]. So, for this study, Campylobacter ssp. was used as the pathogen of reference for the QMRA.

Table 1. Presence of Campylobacter in stored roof-harvested rainwater (RHRW) from different sources.

Samples Tested	Positive Samples	Frequency of Contamination (%)	Concentration (MPN/L)
27	11	40.7%	n.a. [31]
10	1	10.0%	<3–43 [32]
27	10	37.0%	n.a. [33]
100	20	20.0%	n.a. [7]
115	0	0.0%	n.a. [34]
24	5	20.8%	5–100 [35]
17	2	11.8%	n.a. [36]
24	9	37.5%	<0.6–5.6 [37]
32	3	9.4%	26–240 [38]
100	3	3.0%	0–0.056 [20]

2.4. Exposure Assessment

A literature review has been conducted to gather data regarding exposure routes for Campylobacter infection and intake volumes associated with each of the proposed domestic uses for RHRW. Infection routes may include liquid ingestion due to drinking, accidental liquid ingestion due to hose irrigation and food washing, aerosol ingestion due to showering, and direct contact with water.

Volume ingested, and exposure duration and frequency for drinking were taken from the publication titled "Exposure Factors Handbook" from the American Environmental Agency [39]. Parameters of exposure for hose irrigation and food washing were taken from Ahmed et al. [7]. Data for toilet flushing were taken from Ashbolt et al. [40] and Fewtrell et al. [20]. Finally, data from Cohim et al. [17] were used for exposure assessment for bathing.

The input data used for exposure assessment are summarized in Table 2.

Table 2. Risk input values.

Input	Distribution	Mean	Median	Mode	Standard Deviation	Range
Campylobacter concentration (mL)	Lognormal	-	5.6	-	-	0–240
Volume ingested (mL)						
Drinking	Triangular	-	2500	-	-	1400–3600
Bathing (mL/min)	Normal	0.5	-	-	0.2	-
Food washing	Normal	0.5	-	-	0.1	-
Hose irrigation	Lognormal	1.0	-	-	0.1	-
Toilet flushing	Triangular	-	-	0. 1	-	0.01–0.5
Exposure duration (minutes)						
Bathing	Lognormal	-	3	-	-	0.9–44
Frequency of use (#/day)						
Bathing	Lognormal	0.9	-	-	-	0.1–5
Food washing	Triangular	-	4	-	-	2.0–6
Hose irrigation	Lognormal	-	3	-	-	1.0–7
Toilet flushing	Triangular	-	4	-	-	2.0–6

2.5. Dose–Response Assessment

Pathogen ingestion was calculated using Equation (1), based on the probability distributions for parameters from the exposure assessment. The equation used is expressed as:

$$d = N \times Ving, \quad (1)$$

where

d = Dose of pathogens ingested in one exposure ($MPN \cdot day^{-1}$);

N = Pathogen concentration in RHRW ($MPN \cdot mL^{-1}$);

Ving = Volume of RHRW ingested in one exposure ($mL \cdot day^{-1}$).

The mathematical model used to relate the ingested dose with its outcome varies depending on the pathogen considered. A dose–response β-poisson model for Campylobacter ssp. has been developed by Medema et al. [41] and it is presented in Equation (2).

$$Pinf = 1 - [1 + (d/N_{50})]/[2^{1/\alpha} - 1]^{-\alpha}, \quad (2)$$

where

Pinf = probability of infection for one exposure;

N_{50} = microbial dose eliciting 50% infections in the exposed population = 896 [41];

α = slope parameter = 0.145 [41].

2.6. Risk Characterization

Risk characterization encompasses all the previous steps (hazard characterization, dose–response assessment and exposure-assessment) to determine the probability of infection and illness. The annual probability of infection is calculated using Equation (3):

$$Pt = 1 - (1 - Pinf)^{t}, \quad (3)$$

where

Pt = annual probability of infection;

Pinf = probability of infection for one exposure;

t = number of exposures in one year.

To estimate the annual probability of disease, i.e., the number of disease cases per person per year, it has been assumed that 70% of infections result in illness [42], as seen in Equation (4).

$$Pd = K \times Pt, \quad (4)$$

where

Pd = annual probability of illness;

K = disease/infection ratio = 0.7 [42].

Based on the probability of illness, the results of disease cases for each use were transformed in DALY loss per person per year (pppy). We have adopted a value of DALY loss per disease case of 4.6 × 10^{-3} for Campylobacter [42].

The distributions and @Risk input values used in the QMRA are shown in Table 2.

3. Results and Discussion

The risks for the proposed domestic uses for RHRW are summarized in Table 3, both in probability of illness and DALYs pppy.

Table 3. Median values of annual risk for different RHRW uses.

Proposed Water Use	Probability of Illness	DALYs pppy
Drinking	7.39×10^{-2}	3.40×10^{-4}
Bathing	1.41×10^{-4}	6.50×10^{-7}
Food washing	8.70×10^{-5}	4.00×10^{-7}
Hose irrigation	4.57×10^{-5}	2.10×10^{-7}
Toilet flushing	3.04×10^{-5}	1.40×10^{-7}

As expected, drinking untreated RHRW had the highest microbiological estimated risk, with a value of 3.40×10^{-4} DALYs pppy. All the other uses (bathing, food washing, hose irrigation and toilet flushing) had results in the order magnitude of 10^{-7}. Therefore, only drinking untreated RHRW would not satisfy the microbiological risk limit suggested by the WHO for drinking water of 10^{-6} DALYs pppy.

However, there has been a discussion on whether this limit would be the most appropriate, especially for developing countries [43]. The WHO itself admits that this target may not be achievable or realistic in some locations and circumstances in the near term, where the overall burden of disease is high for multiple exposure routes (water, food, air, etc.). In these cases, setting this limit from water-borne exposure alone would not have a big impact on the overall disease burden, and more contextualized values could be established [10]. For Brazil, for example, the risk of drinking untreated RHRW is significantly lower than 1.8×10^{-2} DALYs pppy, which represents the DALY loss from tobacco-related diseases in 2015 [44].

Therefore, to evaluate the severity of consequences from the estimated risks, we adopted the classification proposed by Westrell et al. [45] (Table 4), based on the increase of endemic disease in the community caused by RHRW use. Studies estimate a median value of three to five episodes of diarrhoea per child per year for children under 5 years of age in developing countries [46–51]. We adopted a median value of four episodes of diarrhoea per person per year for Brazil.

Table 4. Suggested definitions of severity of consequences of hazards based on an increase of endemic disease in the community [45].

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

Based on the increase of disease cases (Table 5), drinking RHRW without any treatment would represent a 1.85% increase, with a hazard classified as 'moderate' by Westrell et al. [45].

Table 5. Severity of consequences for the proposed RHRW uses.

Proposed Water Use	Probability of Illness	Increase of Disease Cases	Hazard
Drinking	7.39×10^{-2}	1.85%	Moderate
Bathing	1.41×10^{-4}	0.004%	Insignificant
Food washing	8.70×10^{-5}	0.002%	Insignificant
Hose irrigation	4.57×10^{-5}	0.001%	Insignificant
Toilet flushing	3.04×10^{-5}	0.001%	Insignificant

Once the health risks for the domestic use of untreated RHRW have been estimated, the adoption of measures to increase the quality of rainwater was tested. The adoption of a rainwater first-flush diverter device for the catchment system, and the use of a ceramic water filter, a simple point-of-use treatment for drinking water, were considered given their good public acceptance and due to the fact that they do not require high maintenance for their operation.

Many studies have evaluated the efficiency of rainwater first-flush diverter devices (Table 6), and ceramic water filters (Table 7), showing effective contaminant removal and water quality improvement, proving their potential as measures to improve RHRW quality. Based on the literature, we have estimated the pathogen removal efficiency for Campylobacter of 96% and 93%, for rainwater fist-flush diverters and ceramic water filters, respectively.

Health risk values were then calculated and the hazards were characterized based on the increase of disease cases, considering the adoption of each sanitary barrier and, for drinking water, considering both sanitary barriers (Table 8).

Results show that the estimated health risks for drinking RHRW would drop from 3.4×10^{-4} to 2.92×10^{-5} DALYs and 3.5×10^{-5} DALYs pppy by using the rainwater first-flush diverter and ceramic water filter, respectively. When considered together, it was possible to achieve a risk reduction from 3.4×10^{-4} to 2×10^{-6} DALYs pppy, a significant gain in safety, almost satisfying the WHO guidelines for drinking water, with no need for disinfection through chlorination.

Table 6. Pathogen removal efficiency for rainwater first-flush systems.

Pathogen	Removal Efficiency
Total coliforms	95.5 % [52]
	96.5% [53]
	96.5% [54]
Thermostable coliforms	100% [55]
E. coli	80% [56]
	100% [54]
	100% [53]
	90% [57]
Heterotrophic bacteria	94.39% [52]
Salmonella	100% [57]

Table 7. Pathogen removal efficiency for ceramic water filters.

Pathogen	Removal Efficiency
	97.8% [58]
E coli	85% [59]
	99% [60]
Vibrio spp.	100% [59]
Shigella spp.	93% [59]
Salmonella	86% [59]

Table 8. Median values of annual risk considering the adoption of sanitary barriers.

Proposed Water Use	Sanitary Barrier	Probability of Illness	DALYs	Increase of Disease	Hazard
	First-flush diverter	6.30×10^{-3}	2.92×10^{-5}	0.16%	Minor
Drinking	Ceramic filter	7.61×10^{-3}	3.50×10^{-5}	0.19%	Minor
	Both	4.35×10^{-4}	2.00×10^{-6}	0.01%	Insignificant
Bathing	First-flush diverter	7.83×10^{-6}	3.60×10^{-8}	0.000%	Insignificant
Food washing	First-flush diverter	5.00×10^{-6}	2.30×10^{-8}	0.000%	Insignificant
Hose irrigation	First-flush diverter	2.61×10^{-6}	1.20×10^{-8}	0.000%	Insignificant
Toilet flushing	First-flush diverter	1.74×10^{-6}	8.00×10^{-9}	0.000%	Insignificant

4. Conclusions

Based on a literature survey, we conducted a QMRA study on untreated RHRW use for domestic purposes. Our results indicated drinking RHRW as the only domestic water use that does not conform with the WHO guidelines for drinking water; even so, drinking untreated RHRW would only represent a 1.85% increase in disease cases in Brazil.

The adoption of simple sanitary barriers such as rainwater first-flush diverters and point-of-use treatment systems such as ceramic water filters, has proved to be sufficient to reduce the health risk for drinking untreated RHRW to levels that almost satisfy the WHO guidelines. Such results raise the discussion of adopting a tolerable risk for drinking water that respects regional characteristics, especially in developing countries, to the detriment of chlorination for residential rainwater catchment systems.

Author Contributions: Jálvaro da Hora and Eduardo Borges Cohim collected the data and conducted the Quantitative Microbiological Risk Analysis. Samuel Sipert and Adriano Leão also analyzed the results and contributed by writing the paper in English. The paper was originally written in Portuguese. All authors wrote the paper.

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