Health-risk assessment for roof-harvested rainwater via QMRA in Ikorodu area, Lagos, Nigeria

Chukwuemeka Kingsley John, Jaan H. Pu, Rodrigo Moruzzi and Manish Pandey

ABSTRACT

This paper presents a study to assess the roof-harvested rainwater (RHRW) in the Ikorodu area of Lagos state, Nigeria, and recommends guidance to minimise the health risk for its households. The types, design and use of rainwater harvesting systems have been evaluated in the study area to inspect the human risk of exposure to *Escherichia coli* (*E. coli*). To achieve these objectives, a detailed survey involving 125 households has been conducted which showed that 25% of them drink RHRW. Quantitative microbial risk assessment (QMRA) analysis has been used to quantify the risk of exposure to harmful *E. coli* from RHRW utilised as potable water, based on the ingestion of 2 L of rainwater per day per capita. Results have revealed that the maximum *E. coli* exposure risk from the consumption of RHRW, without application of any household water treatment technique (HWTTs) and with application of alum only, were 100 and 96 respectively, for the estimated number of infection risk per 10,000 exposed households per year. This estimation has been done based on 7% of *E. coli* as viable and harmful. Conclusively, it is necessary that a form of disinfectant be applied to the RHRW before use.

Key words | *Escherichia coli* (*E. coli*), household water treatment technique (HWTT), quantitative microbial risk assessment (QMRA), questionnaire survey, roof-harvested rainwater (RHRW)

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HIGHLIGHTS

- It consists of a case study of roof-harvested rainwater at Ikorodu area of Lagos, Nigeria.
- The QMRA analysis has been used to quantify the risk of infection associated with the exposure to potential pathogens from roof-harvested rainwater.
- This paper presents a pilot rainwater quality study at the investigated area, which involves a detailed household surveying technique to acquire the needed research information.

INTRODUCTION

In the 2012 millennium development goals report, Nigeria was listed as one of the nations with lack of access to a drinkable water source. It has been stated by WHO/UNICEF JMP (2012) that Nigeria has limited or no progress for its sanitation facilities. Despite Nigeria narrowly meeting the target for improved drinking water, the report showed that most of these improvements were recorded in urban areas. Access to clean drinkable water in Lagos state is low, with most residents depending on individual harvesting sources such as well, rainwater, borehole and river (Balogun *et al.* 2017). Harvested rainwater has the potential to improve access to a water source, therefore it is imperative to

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investigate its impact, especially where there is limited access to pipe-borne treated water.

Sediment, pollutant and saline from natural and man-made terrains or channels (Pu 2016; Pu 2019; Obianyo 2019; Ekwueme & Agunwamba 2020; Pu *et al.* 2020) can significantly contaminate drinking water, where those sources are complex depending on their effective settling and mixing within water (Pu *et al.* 2014, 2016; Pu 2015, 2021). Besides, the watershed and climate issues can also impact the pollutant content within water resources (Guiamel & Lee 2020; Javadinejad *et al.* 2020). These sources further hinder the effort to disinfect drinking water, and this can be disastrous for the least developed areas in the world where disinfected drinkable water is still not widely available. Roof-harvested rainwater (RHRW) has been increasingly adopted as an alternative water supply source for domestic use in developing countries. However, the presence of microbes in the harvested water has made it dangerous to use. Recognising the consumption of untreated contaminated water to be one of the notable pathways for pathogens transmission to humans, this study provides a crucial assessment for the health risks involved in ingesting untreated water.

Two common methods have been identified by several studies for quantifying microbial risks in drinking water: quantitative microbial risk assessment (QMRA) and epidemiological approaches (Calderon *et al.* 1991; Whelan *et al.* 2014). The QMRA explicitly defines the origin of faecal pollution, the fate and kinetics of the microbes, the natural variability of the microbes in environmental matrix and the etiological agent; while the epidemiological approach informs the propensity of these factors implicitly (Whelan *et al.* 2014). Various studies have also shown that QMRA gives good interpretation to the epidemiological results by generating the estimate of human-health risk, where an epidemiological study can be impractical (Pruss *et al.* 2002; Whelan *et al.* 2014). Furthermore, some other studies (i.e. Calderon *et al.* 1991; Roser *et al.* 2006; Soller *et al.* 2006, 2010; Ahmed *et al.* 2010; Whelan *et al.* 2014) investigated the use of QMRA in evaluating the possible health risk associated with: (1) the use of water for ingestion and other purposes such as recreation and bathing; (2) swine, dog, cattle, fresh gull, sea gull and cattle faeces and primary sewage; and (3) human enteric viruses. Those studies estimated the possible risks using four different sets of information: hazard identification; dose response; exposure assessment; and risk characterisation and management (Haas *et al.* 1999; Hunter *et al.* 2003; Ahmed *et al.* 2010; Whelan *et al.* 2014). Studies have also been conducted to investigate potential microbial risks in harvested rainwater based on the presence of microbes in rainwater storage tanks (Lye 2002; Schets *et al.* 2010; Soller *et al.* 2010; Vialle *et al.* 2012; Lim & Jiang 2013; Whelan *et al.* 2014). They determined the microbial health risk using several pathogens, including the pathogenic strains of *Escherichia coli* (*E. coli*), *Camplyobacter* spp., *Cryptosporidium* spp., *Enterococci* spp., *Legionella pneumophila*, *Salmonella* spp., *Clostridium perfringens* and *Giardia* spp. These pathogens have been found in rainwater storage tanks tested in different parts of the world (such as USA, Holland, Denmark, Greece, Uganda, France and Australia). Also, it can be observed that these studies used different bacterial enumeration methods, i.e. qPCR, PCR, membrane filtration and Colilert methods, and different numbers of rainwater samples (Gerba *et al.* 1996; Ahmed *et al.* 2010; Lim & Jiang 2013; Machdar *et al.* 2013; Whelan *et al.* 2014). This implies that QMRA can be carried out using a wide range of pathogen enumeration methods and relatively varying water samples.

There is a lack of access to clean water in Lagos, including Ikorodu, and the dependency on rainwater is high (Longe *et al.* 2010; Balogun *et al.* 2017). Therefore, it is important to assess the health risk of drinking RHRW. In this paper a pilot study was performed through QMRA in the Ikorodu area in order to assess the pathogenic bacteria risk from consuming roof-harvested rainwater, which is one of the area's common practices. By doing this, this paper aims to conduct a useful study to alert the authorities and community about the risks and safety practices for the sustainable and secure consumption of rainwater. Pathogenic strains of *E. coli* have been used to develop the QMRA as suggested in previous studies (Soller *et al.* 2010; Abia *et al.* 2016). Furthermore, in this study, the quality of roof-harvested rainwater (RHRW) and different scenarios obtained from the field-work survey have been used to estimate the risks posed by exposure to *E. coli*. A survey of structured questionnaires was delivered to 125 households to collect the relevant data, and the households were chosen to cover the whole study area. This study analysed the results from the questionnaires and expanded the analysis into the whole population of the study area. The information from the survey and enumerated bacteria were coherently applied to assess the health of the population who consumed untreated harvested rainwater. These will be discussed in the following two main sections: Materials and method, and Results analysis.

MATERIALS AND METHODS

The study area and administration of questionnaire

The study area is the Ikorodu Local Government Area of Lagos, Nigeria. It is situated in the northern part of Lagos, approximately located in longitudes 3°30′E and latitude 6°36′ (Umunnakwe *et al.* 2019). This area has been chosen because of the inhabitants' dependency on rainwater, especially during the rainy season; and it is also one of the fastest developing areas in Lagos (Longe *et al.* 2010). This area also has various commercial and retail institutions, residential buildings and public and private institutions, hence rainwater collection can impact those different communities. This fact makes the proposed research both challenging and important for the study area.

A house-to-house surveying method was used to administer the household questionnaires in a mixture of good and poor sanitation areas. This method was chosen because of the availability and ease of access to each household in the area, and the difficulty of obtaining detailed information through the internet. The sampling error was statistically calculated to be around 0.5%. The map and population status of the area were analysed, and a visual inspection was conducted before classifying the regions. The questionnaires were administered to a person between the age of 25 and 50 in each of the interrogated households with support from the authors to explain the questionnaires to ensure accurate response from the households. The questionnaire household's distribution is presented in Figure 1.

A total of 125 questionnaires were collected, and on average there are about 4.9 persons in each household. Among a total of 613 people, 11% were younger than five years old; while only 1% were older than 60 years of age. This information is important as ingestion of pathogens may more severely impact these groups. These demographic results, together with the amount of pathogenic strains of *E. coli* ingested from the rainwater storage tank, were used to develop the QMRA.

In this study, each household was interrogated once, and each questionnaire was monitored to be fully answered. The survey results were analysed in two stages: (1) strategy of water use, and (2) water and sanitation infrastructure. A sample of the questionnaire can be found in Appendix A.

Figure 2 presents a summarised flow chart for the methodology used in this study. First, the questionnaires were distributed to different parts of Ikorodu. At the same time, the samples were taken and the bacterial counts for the RHRW were carried out using the Colilert-18 method to determine the exposure assessment of *E. coli* to the people. Then, the information obtained from the analysis of questionnaires and the enumerated *E. coli* were used to develop the proposed QMRA analysis. Finally, the analysis of QMRA was concluded and recommendations were proposed.

Development of the QMRA

The development of QMRA involves a four-phase process to estimate the human health risk associated with exposure to the target pathogen. The utilised method is described by Gerba *et al.* (1996) and Ahmed *et al.* (2010). The four phases include: (i) hazard identification; (ii) exposure assessment; (iii) dose-response assessment, and (iv) risk characterisation. These phases are described as follows.

Hazard identification

This phase was achieved by collating the presence of target pathogens in different household water treatment techniques (HWTTs). The enumeration of target pathogen in both the harvested rainwater tanks and the roof were assessed using the standard Colilert-18 method (i.e. APHA protocol number 9223 B. Enzyme substrate test). This phase represents an initial assessment of data, and it is evaluated more meticulously in the subsequent QMRA phases to fully identify and categorise all the risks involved in drinking rainwater. One of the main emphases of this phase is to decide if there is enough information to consider a

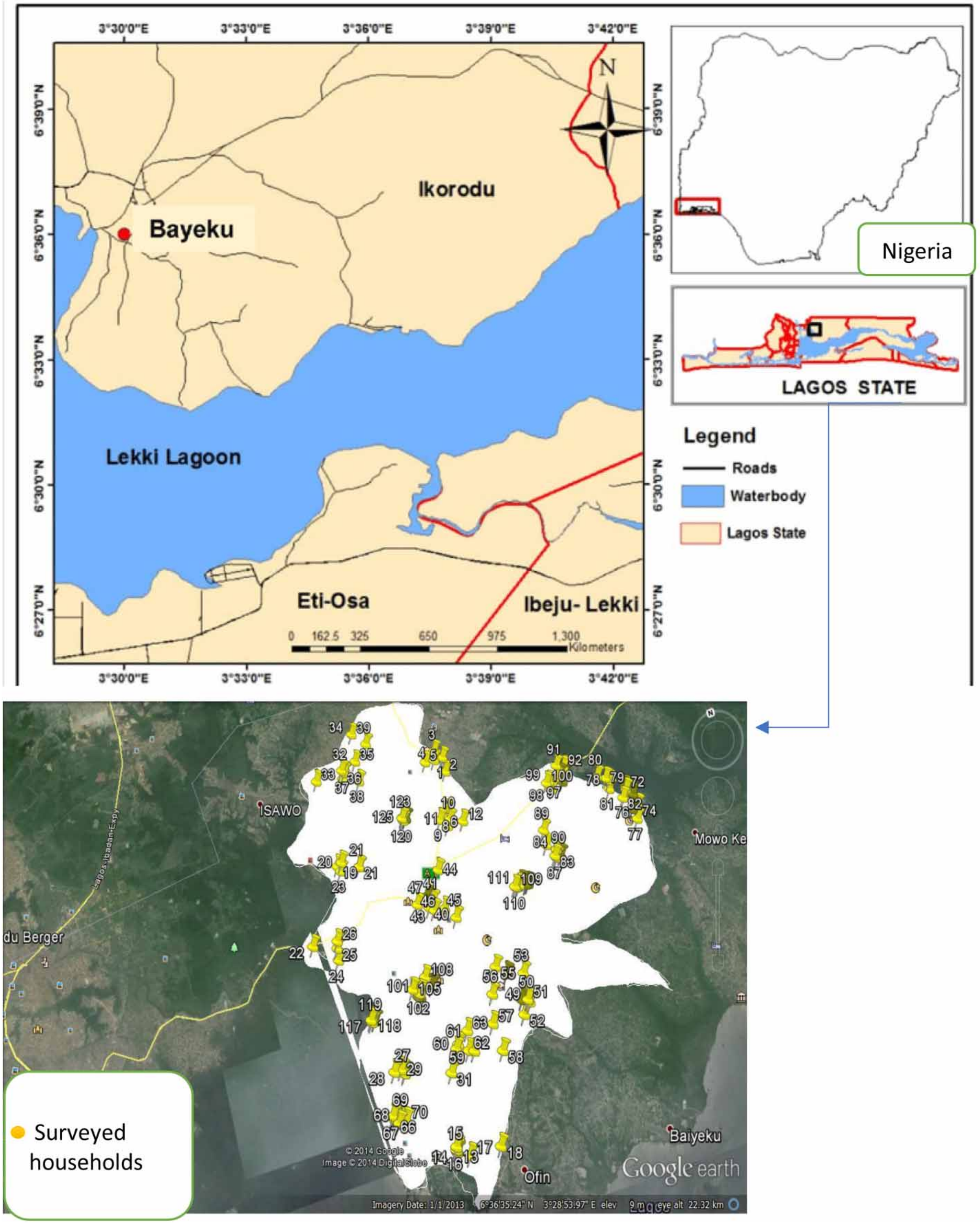

Figure 1 | Cross-sectional map of Lagos state showing the location of Ikorodu and the areas of administered questionnaires (Google Earth 2013; Umunnakwe *et al.* 2019).

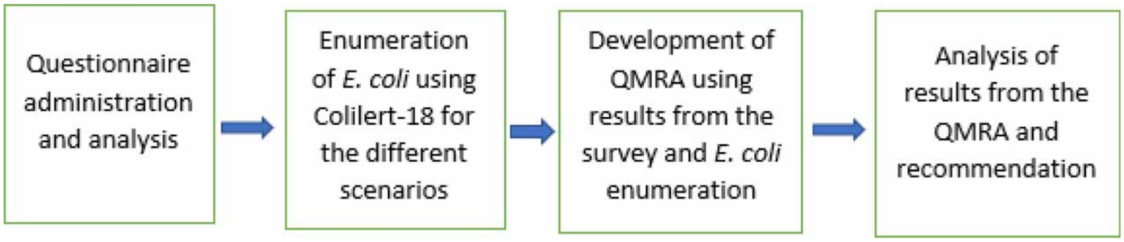

Figure 2 | Flow chart of the methodology.

substance (e.g. *E. coli*) as the cause of adverse health, e.g. causing diarrhoea (Ahmed *et al.* 2010). The following sections describe the target pathogens and the sampling methods used in this phase of study.

Studied pathogens

E. coli was used as the target pathogen for this study due to their significance in water-borne human health issues. *E. coli* is a type of bacteria usually detected in the stomach of humans and animals, and there are hundreds of strains of *E. coli* (Weaver *et al.* 2015). A few strains, such as *E. coli* O157:H7, are found to produce harmful toxins which cause severe illness to humans. The maximum range of these harmful strains of *E. coli* is 0–7% (Ahmed *et al.* 2010). This study assessed the QMRA of RHRW using 7% of harmful strains of *E. coli*, which agreed with Machdar *et al.* (2013) who used 8%. The patients who are infected with *E. coli* O157:H7 face a 30% higher risk of kidney failure or high blood pressure (Kanarat 2004; Lim & Jiang 2013). These patients could also experience severe abdominal cramping or bowel necrosis (tissue death), and there is likelihood of stroke or seizure. In some cases, the patient may be afflicted with bloody diarrhoea and its symptoms could appear within hours to 10 days of infection. Also, in a few cases, the afflicted patients show no symptoms and can pass it on to people who later become sick (Kanarat 2004; Lim & Jiang 2013).

Sampling methods

The Colilert-18 method was used to enumerate the bacterial counts for all the investigated 49 different rain events in both rainy and dry seasons (the details of all the observed rain events can be found in Appendix B). This sampling exercise was used as it was proven by the manufacturer's analysis to be reliant, and it aimed to provide good statistical confidence in terms of the sample size. The Colilert-18 tests were executed in accordance with the manufacturer's guidelines. Initially, 100 mL of the sample was added into IDEXX's dehydrated media in the supplied sterile jars. The samples were shaken by hand 3–4 times over 6 minutes to dissolve the media. The contents of the jars were then emptied into sterile quanti-trays and heat sealed with a sealer. The quanti-trays were then incubated at 35 °C for 18 hours. Following incubation, the quanti-trays were compared to the supplied comparator. The quanti-trays were then placed in the fluorescing wells (366 nm), where the number of *E. coli* cells was measured.

Exposure assessment

In this second phase of QMRA, the number of the pathogenic strains of *E. coli* in the rainwater storage tank and the volume consumed by a person were estimated. The pathogens number was inserted into the dose-response models to estimate the possibility of infection. The exposure assessment also determined the magnitude and period of exposure by each pathway and estimated the number of people exposed as well as the categories of people affected (Petterson *et al.* 2007; Whelan *et al.* 2014). The pathway considered in this study included the enumerated microbes before and after application of different HWTTs.

Dose-response assessment

This phase was used to assess the risk of a response for a known dose (number of microbes) of target pathogen. The dose-response models are statistical equations that define the dose-response association to target pathogen, transmission routes and hosts. The statistical model for predicting dose-response has been developed using data sets from several previous human and animal studies (Petterson *et al.* 2007; Whelan *et al.* 2014). In this study, the amount of pathogenic strains of *E. coli* consumed before and after the application of different HWTTs was determined and used to estimate the probability of illness for the population.

The dose-response relationship has been investigated in various studies (e.g. Gerba *et al.* 1996; Ahmed *et al.* 2010; Whelan *et al.* 2014), which recommended either the Exponential or Beta-Poisson model to assess such a relationship. Strachan *et al.* (2005) further suggested that the Exponential model presented the best fitting results to protozoa and viruses, while the Beta-Poisson model gave better fit to bacteria. Since the pathogenic strains of *E. coli* were used as the target pathogen in this study, the Beta-Poisson model was used as follows.

$$P(i) = u\left(1 - \left[1 + \left(\frac{d}{\beta}\right)\right]^{-\alpha}\right) \tag{1}$$

$$N = 10{,}000P(i) \tag{2}$$

where $P(i)$ in Equation (1) denotes the probability of infection per 10,000 persons in Ikorodu in the exposed population for a single event while d denotes the dose (i.e. number of infective units); u in Equation (1) denotes the percentage of *E. coli* strains that are viable and harmful (it is taken as 7% in this study). In Equation (2), N denotes the number of infections per 10,000 persons for a single event and α and β are the best-fit parameters in the Beta-Poisson model, which are used as 0.3126 and 2884 respectively, as suggested through field and experimental observations by Haas *et al.* (1999), Ahmed *et al.* (2010), and Lim & Jiang (2013). This model assumes that the probability of infection per consumed pathogen varies within the exposed population due to the variation in human response and pathogen competence (Haas *et al.* 1999).

According to Haas *et al.* (1999) and Leite & Moruzzi (2016), an accurate dose-response model for risk assessment should have wide characteristics, including: (1) well-imitation to human pathophysiology; (2) ability to analyse the exposure path similar to natural infection; (3) having preference for infection as a response compared to the detriment symptoms or death; (4) having a strain of the pathogen similar to the infection cause; (5) having statistically acceptable adjustment (do not reject null hypothesis, $p > 0.05$, for 95% significance); (6) modelling with data gathered through two or more experiments with statistically similar data sets; and (7) having low average infectious dose quotient per average lethal dose in order to obtain a conservative risk estimate. In summary, it is difficult to find a single model with all the features listed, thus, it is crucial for each user to use the model that suits their usage the most (Leite & Moruzzi 2016).

According to Ahmed *et al.* (2010), data monitoring for a QMRA can be obtained from direct measurement of the pathogen, derivation from indicator bacteria, or estimation from a distribution fit. The data used in this study was determined by direct enumeration of *E. coli* in the water samples. The *E. coli* exposure and risk scenarios were obtained from the well-structured questionnaires.

Risk characterisation and management

The first three phases provided a range of values under Monte Carlo analysis, where the results presented a full range of possible risks from the average to worst-case scenarios. The fourth phase of risk characterisation and management was utilised to integrate information from the amount of doses received (from the exposure assessment) and the risk associated with different doses (from the dose-response assessment), in order to estimate the probability of risk. This involved gathering of information from the first three phases into a single statistical model to calculate risk.

The probability and number of risk infection per 10,000 people in Ikorodu per year was obtained by using Equations (3) and (4), respectively (Haas *et al.* 1999):

$$P_N = 1 - [1 - P(i)]^E \tag{3}$$

$$N = 10{,}000P_N \tag{4}$$

where P_N in Equation (3) is the probability of infection per 10,000 rural Ikorodu person per year for different scenarios for a single event; E denotes the number of exposure events per year and the value of E was taken to be 281, which was obtained from the average of the total number of days in the rainy season (April–October).

As part of QMRA, risk management has been considered. Risk management aimed to mitigate or eliminate risks and their associated negative outcomes. Risk management can be performed using different strategies and is most effective when it is informed by risk characterisation (Petterson *et al.* 2007; Whelan *et al.* 2014). The risk management in this study included investigating the impact and use of different HWTTs, besides recommending the most effective treatment method.

E. coli as targeted pathogen: advantages and limitations

The assessment of microbiological quality of drinking water relies on the presence of indicator bacteria such as coliforms and *E. coli*. *E. coli* is a member of the faecal coliform group and is a more specific indicator of faecal pollution than other faecal coliforms (Ahmed *et al.* 2019). There are a number of *E. coli* strains and most of them are harmless. However, some *E. coli* strains, such as Shiga, are toxin-producing *E. coli*, and can cause severe illness (WHO 2016). It is acknowledged that *E. coli* concentrations do not necessarily correlate to pathogens. In this study, the QMRA of the RHRW was assessed using 7% of the enumerated *E. coli* since the study by Ahmed *et al.* (2010) showed that the proportion of harmful *E. coli* strains is between 0 and 7%, and a similar outcome on harmful *E. coli* proportion has been reached by others, such as Machdar *et al.* (2013). The reasons *E. coli* was chosen to monitor microbes are its feasibility and ability to represent the potential presence of pathogen and their ease of analysis (WHO 2016). A major limitation of using *E. coli* is that they do not always imply the presence of pathogens in environmental waters. Having said that, the major part of the disease burden may originate from *E. coli* strains (Machdar *et al.* 2013), and hence it is still popularly used for assessing the microbial contamination of drinking water (Petterson *et al.* 2016; WHO 2016; Ahmed *et al.* 2019). Moreover, it must be stressed that *E. coli* may be a strong indicator when poor sanitation measures are applied, which is common in low-income countries, with serious risk of contamination for children and the older generation.

In a study conducted by Petterson *et al.* (2016) to evaluate rainwater treatment systems with respect to human health risk from faecal pathogens, it was stated that general faecal indicator bacteria (such as *E. coli*) can be used as a preliminary screening tool before testing other pathogens. Also, the proportion of these indicator bacteria to pathogens are sometimes used for risk assessment purposes (Petterson *et al.* 2016). It must be stressed that the presence of *E. coli* is a better indicator of the potential presence of enteric pathogen than the absence of *E. coli* (WHO 2016).

Experiments on different scenarios

In this field study, rainwater was collected directly into a 255 L tank via a 2.5 m gutter, and 5 L of the water samples were collected from the top of the tank on cessation of the rainfall event. This level was selected because residents from the study area collect water from the top of the tank via cups/jugs, and do not store the harvested rainwater for long periods. The storage tank and water sample container were washed with sterilised water and emptied after the harvest of each rain event to prevent contamination. This was carried out to ensure that the storage tanks were bacteria-free before the harvest of the next rainfall.

The experiment was performed to enumerate the amount of *E. coli* both before and after the application of different HWTTs. The HWTTs considered in this study include alum, chlorination, boiling and the combination of chlorination and alum, and these are the HWTTs used by the residents in the study area. The pH range of the harvested rainwater was between 5.5 and 6.5. Also, the raw sample was analysed for *E. coli* before the application of each HWTTs for each rainfall event. Details for each HWTT are discussed below:

- Alum: 28 g of the powdered alum was weighed, mixed and dissolved into 1 L of raw water sample in accordance with the manufacturer's instruction. Rapid (110 rpm) and slow (40 rpm) mixing was applied for 3 and 25 minutes respectively, and the water sample was allowed to settle for 1 hour. The water sample was then filtered and analysed for *E. coli*.
- Chlorination: Sodium hypochlorite was used as a source of chlorination. Fifteen grams of powdered sodium hypochlorite was weighed and dissolved into 1 L of the raw

water sample following manufacturer's guidance. The water was allowed to settle for 1 hour before the process to analyse *E. coli*.

- Boiling: One litre of the rainwater was boiled for 10 minutes to 100 °C. The water sample was allowed to cool for 30 minutes and then analysed for *E. coli*.
- Chlorination and alum: A combination of alum and sodium hypochlorite was applied to the water to investigate its impact. Fifteen grams of powdered sodium hypochlorite and 28 g of the powdered alum were used. Rapid and slow mixing took place, and the treated water sample was allowed to settle for 1 hour before being analysed for *E. coli*.
- No HWTT: This scenario involves analysing the raw water sample for *E. coli* using the Colilert-18 technique.

RESULTS ANALYSIS

Analysis of the questionnaire

The survey results were analysed in two stages: (1) strategy of water use, and (2) water and sanitation infrastructure. Their analyses are presented in the following sections.

Water use strategy

Results from the analysis of questionnaires showed that boreholes are the major source of drinking water throughout the year. However, the proportion of respondents that use boreholes reduced from 82% in the dry season to 55% in the rainy season (see Figure 3), thus highlighting the importance of rainwater. The work of Longe *et al.* (2010) showed that approximately 20% of Nigeria's population (34 million) harvest rainwater during the rainy season. Contradictory to Nigeria as a whole, the result from the Ikorodu area shows that the dependency on rainwater is quite high since 114 surveyed households (out of 125) harvest rainwater (either to drink or use). Furthermore, 31 of the 114 rainwater harvesters drink the rainwater (Figure 3); while six of the 31 rainwater drinkers admitted drinking untreated rainwater (Figure 4). The remaining 83 households harvest rainwater to use for daily activities such as farming, washing clothes and dishes, bathing and for other domestic needs. Despite the dependency on rainwater, the results showed that the storage time for all harvested rainwater is relatively short (between 2 days and 1 week depending on the size of family). The information about the household rainwater treatment was used to estimate the health risk via QMRA for different categories of rainwater drinkers in the population.

Water and sanitation infrastructure

The sizes of storage tanks are shown in Figure 5. Among smaller rainwater tank (20–225 L tank) users, 77 households (about 76%) believed that there will be more contamination if the harvested rainwater is stored for

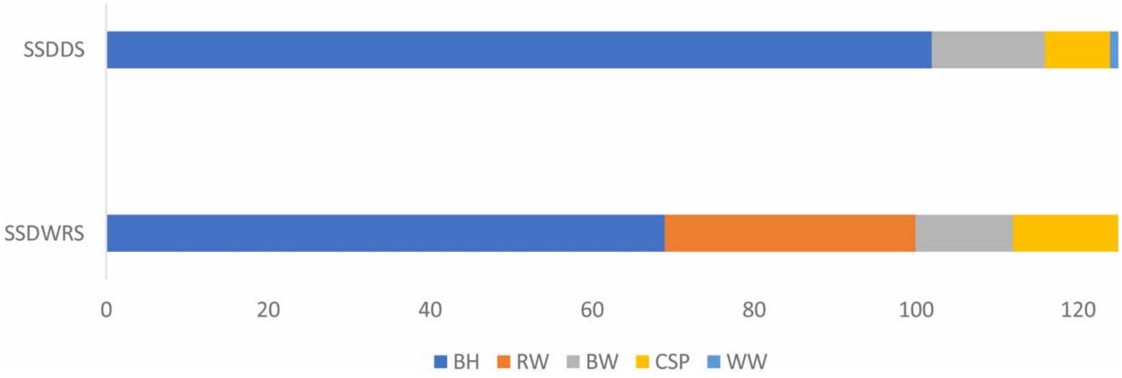

Figure 3 | Sources of drinking water in the rainy and dry season respectively (BH, RW, BW, CSP and WW denotes boreholes, rainwater, bottle water, community stand-up pipes and well water respectively; while SSDWRS and SSDDS denotes sources of drinking water in the rainy season and sources of drinking water in the dry season respectively).

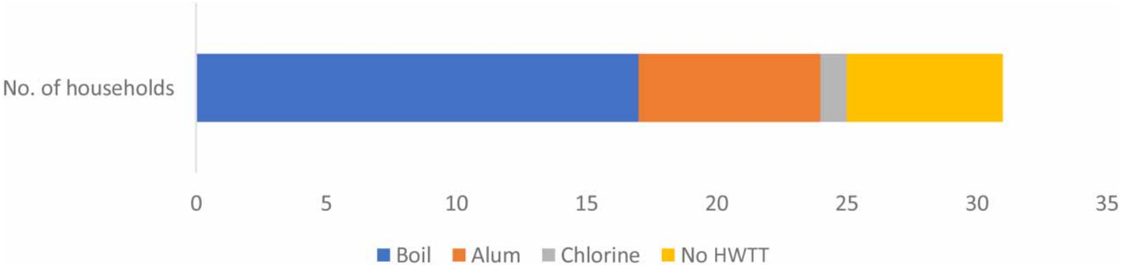

Figure 4 | Number of households that drink rainwater per HWTT.

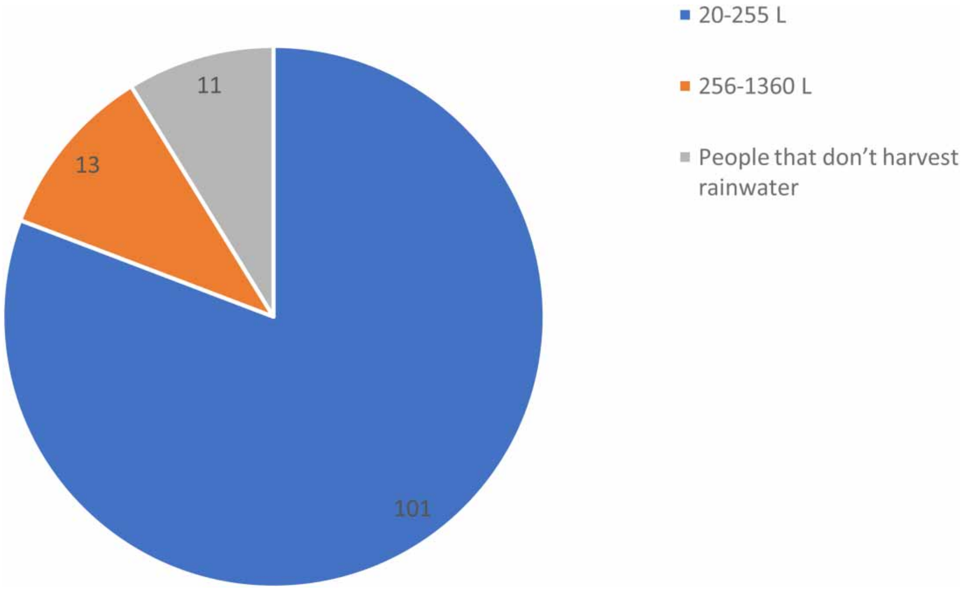

Figure 5 | Sizes of storage tanks.

longer periods; while the remaining 24 households (about 24%) who harvested rainwater do not have any preference for rainwater's storage time. Furthermore, 25 of the 31 harvested rainwater drinkers (i.e. 81%) claimed that they were aware of rainwater contamination and applied one form of HWTT; while the remaining six (i.e. 19%) were without any form of treatment (Figure 4). These data were linearly extrapolated to the overall population of Ikorodu to estimate the percentage of total population that is exposed to harmful strains of *E. coli*.

The roof types on the buildings of the inspected households and people who drink rainwater are presented in Figure 6, while the rainwater harvesting techniques employed by all the people who harvest, and drink rainwater are illustrated in Figure 7. The results showed that 83% of the rainwater harvesters gather it from the roof-top into a collection vessel (and later transfer it into the storage tank), while the remaining 17% collect the rainwater directly into the storage tanks. Further analysis showed that 88% of all the roofs were corroded, of which 84% of those belonged to rainwater drinkers. This fact is important because previous studies have shown that contamination of RHRW can be caused by aged roof materials (Uba & Aghogho 2000). The studies also stated that the amount of a roof's reactive materials with rainwater could be dependent on the air quality of the harvest area.

The statistics of the first flush practice by the rainwater harvesters is shown in Figure 8. It is crucial as several

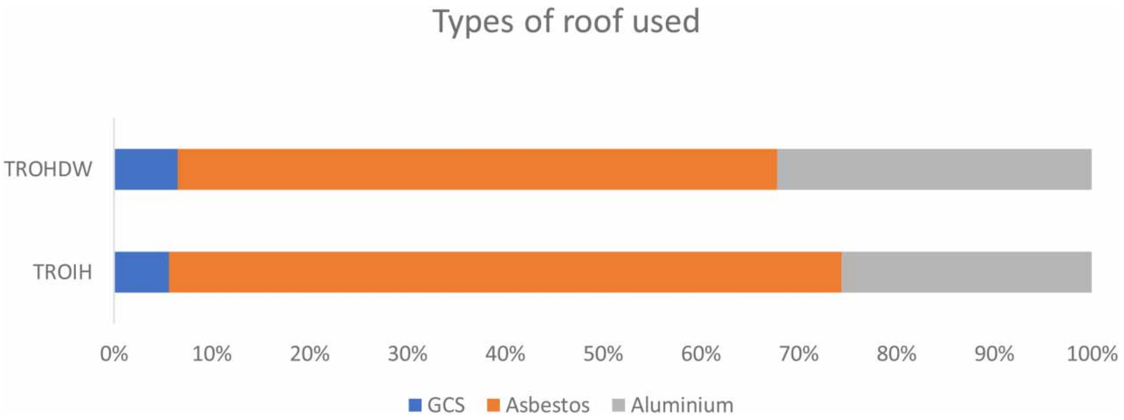

Figure 6 | Type of roofs used by the residents of Ikorodu (TROHDW and TROIH denotes type of roofs owned by the households which drink rainwater and owned by all the interrogated households respectively, while GCS denotes galvanised corrugated sheet).

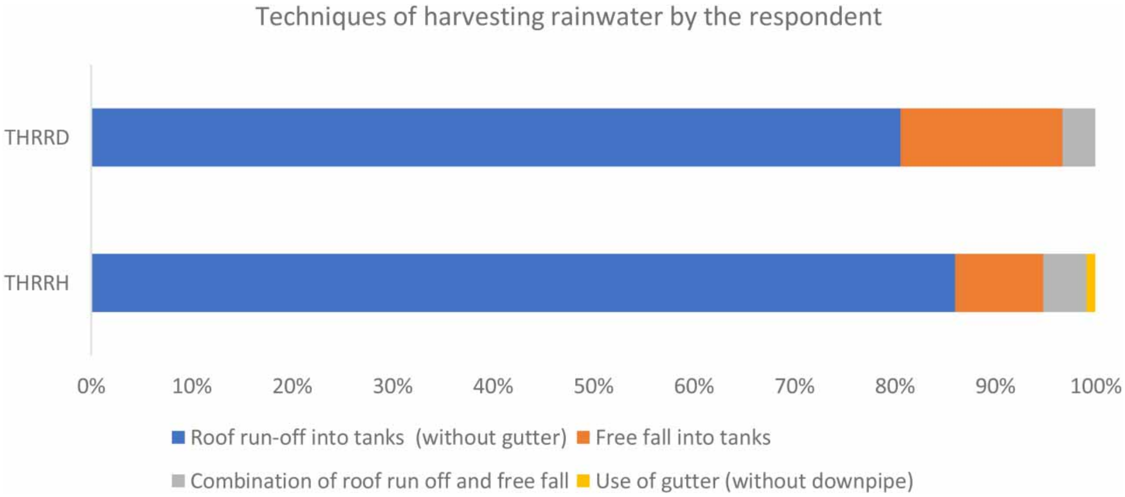

Figure 7 | Techniques of harvesting rainwater by respondent (THRRD and THRRH denote the techniques of harvesting by rainwater drinkers and the techniques of harvesting by rainwater harvesters respectively).

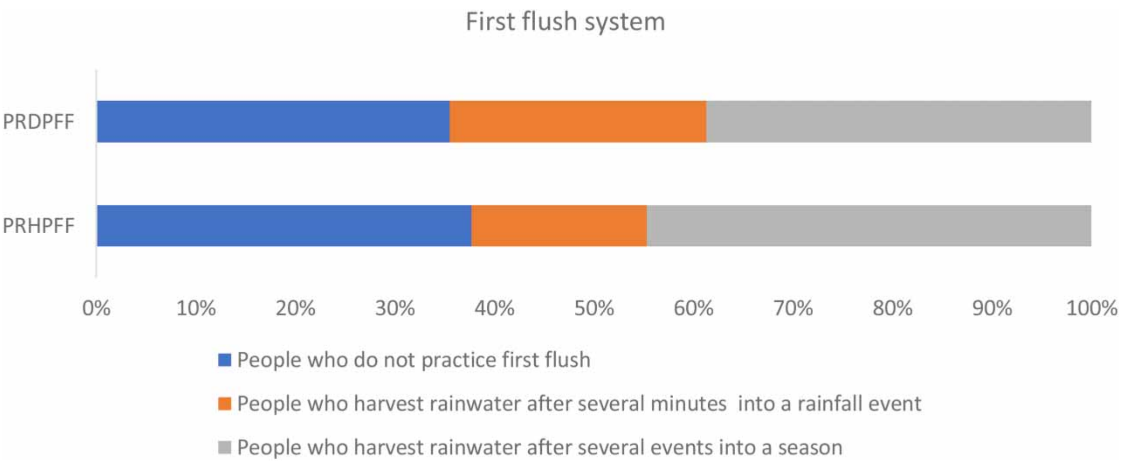

Figure 8 | Proportion of rainwater harvesters/drinkers that practice first flush (PRDPFF and PRHPFF denote proportion of rainwater drinkers that practices first flush and proportion of rainwater harvesters that practices first flush).

studies have proven that the quality of RHRW improves with first flush (Kus *et al.* 2010; Amin *et al.* 2013). The results showed that none of the households have the automated first flush devices; however, some of them practised first flush in a few different ways. While some harvested the rainwater after several minutes into a rainfall event, others harvested after several rainfall events into the rainy season (Figure 8). The practice of first flush is particularly important for people who drink rainwater as it helps to reduce contamination from the roof-top.

The results from the survey also suggest that the hygiene and sanitation of the area is generally poor. Due to an absence of effective drainage systems, among the 125 households that participated in this survey study, 90% (113) of the households claimed they dispose of their greywater on the ground around their building. This encourages the evaporation of greywater and its downward infiltration towards the groundwater. Both mechanisms are likely to leave a residual solid waste within the first few millimetres of soil. Furthermore, for most households, the distance between where they keep their storage vessel and their toilets was generally less than 10 m, thereby suggesting the probability of transmittance of microorganisms. Also, it was observed that boreholes used for potable supply were often dug at places close to septic tanks, which has a risk of contaminating the borehole especially for the shallow water table.

Results

Development of the QMRA model

The information needed to develop QMRA in order to characterise the *E. coli* exposure risk includes the average pathogen densities, average water ingestion for exposure scenario, dose-response relationships for pathogens, and conditional probability of illness (Gerba *et al.* 1996; Hunter *et al.* 2003; Whelan *et al.* 2014). The results presented in Table 1 demonstrate the estimated pathogenic *E. coli* doses that were ingested from different HWTT scenarios in Ikorodu. The number of pathogenic *E. coli* obtained from the Colilert-18 method over 49 rain events was 1.55 MPN/100 mL before the application of different HWTTs; while the number reduced to 0.78 MPN/100 mL with alum application (Table 1). No *E. coli* was detected in other applied HWTTs, i.e. boiling, chlorine and combination of alum and chlorine, as boiling and chlorine act as disinfectants in those techniques.

Table 1 | Estimated pathogenic *E. coli* doses for different investigated HWTTs

S/N	HWTTs applied	*E. coli* dose (MPN/100 mL)
1	Boil	–
2	Alum	0.78
3	Chlorine	–
4	No HWTT	1.55
5	Alum + chlorine	–

The probabilities ($P(i)$) and numbers (N) for different scenarios were calculated using Equations (1) and (2) respectively and are presented in Table 2. In Figure 9, the normalised N values are plotted against the number of estimated infective units (log(d/50)). The figure illustrates the dose-response phase and assesses the risk of response given a known dose (number of microbes) of the target pathogen. It shows the correlation between the probability of infection in the exposed population and administered dose. The results from Tables 1 and 2 have proven that it is crucial to apply disinfectant to eliminate any harmful *E. coli* in the harvested rainwater. An exponential relationship has been observed between the pathogenic *E. coli* doses and the calculated probability of infection (i.e. an increase in the consumed *E. coli* dosages led to a significant increase in the numbers of infection).

In the risk characterisation of the final phrase, the numbers exposed to pathogenic *E. coli* per 10,000 persons in Ikorodu was estimated. Figure 10 shows the employed methodology to estimate the proportion of persons who were affected by harmful *E. coli*. The figure presents each

Table 2 | Probabilities and numbers of infection per 10,000 rural Ikorodu inhabitants for different scenarios per single event

S/N	HHTTs applied	*E. coli* dose in 2,000 mL (MPN)	$P(i)$ %	N
1	Boil	–	–	–
2	Alum	15.54	0.0118	0.118
3	Chlorine	–	–	–
4	No HHTT	31.08	0.0234	0.234
5	Alum + chlorine	–	–	–

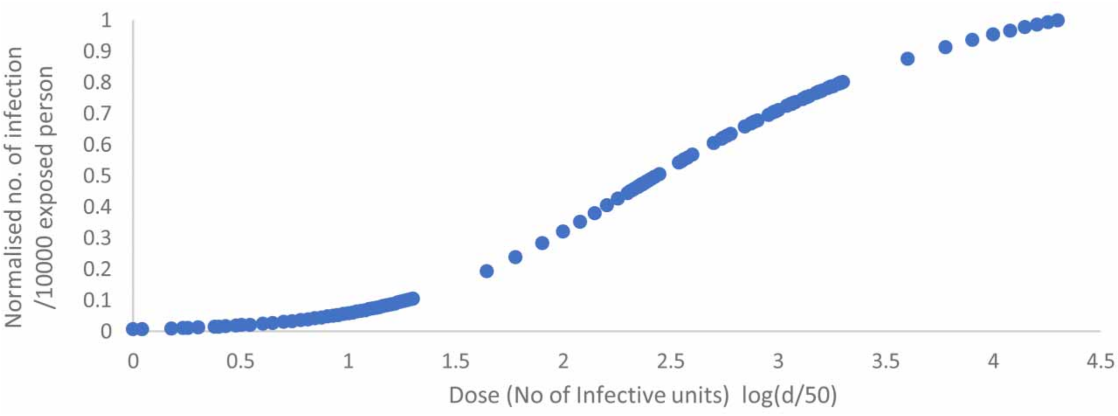

Figure 9 | Beta-Poisson dose-response relationship. The dose-response relationship correlates *N* to *P*(*i*).

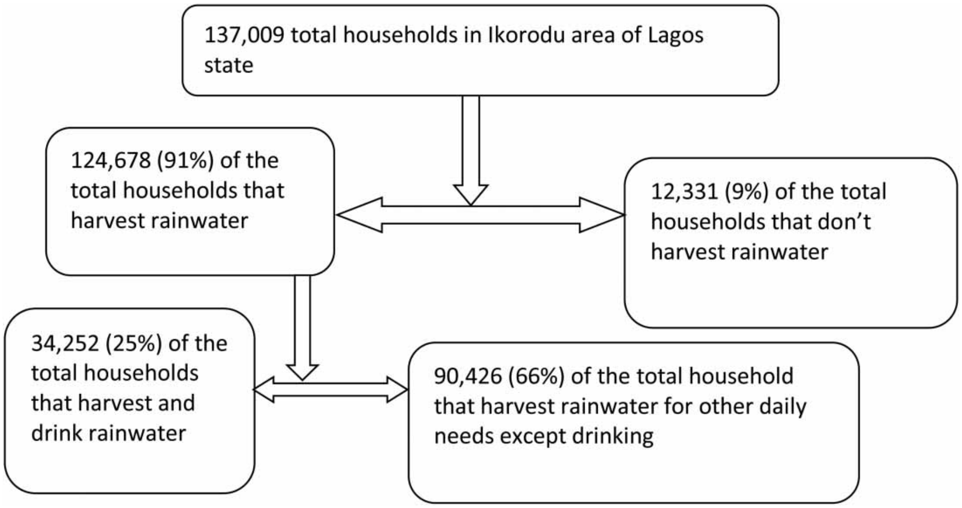

Figure 10 | Household number estimation for rainwater users (the percentage in the chart were estimated from the survey outcome).

estimated group (i.e. who did or did not harvest rainwater; and who did or did not drink rainwater) from the total population. From the total population of 685,045 persons, which averaged to 137,009 households, the survey estimated that 91% of the total households harvested rainwater. Furthermore, Figure 10 also illustrates the adjusted percentage of households that applied different forms of HWTT. The results from Table 3 suggest that 34,252 households in Ikorodu harvested and drank rainwater during the rainy season, while almost 5% of the total households do not apply any form of HWTT. This implies that a significant number of households may be at exposure risk to the target pathogen found in the rainwater storage tank.

Table 3 | Survey results of different HWTTs (including no HWTT) on rainwater drinkers

S/N	HHTTs	% of households who drink rainwater to the total household population	Household population of rainwater drinkers
1	Boil	13.7	18,770
2	Alum	5.6	7,741
3	Chlorine	0.8	1,096
4	No HWTT	4.9	6,645
	Total	25	34,252

In a worst-case scenario, *E. coli* can present in the rainwater storage tank for 281 days in the rainy days of a year. It is found that this was an overestimation since it was very

Table 4 | Infection risk for individuals exposed to contaminated tank water for four different HWTTs

HHTTs	Maximum Ps (%)	Maximum Rs	Number of events per year	Maximum Py (%)	Maximum Ry
Boil	–	–	–	–	–
Alum	0.0118	118	281	0.00964	96
Chlorine	–	–	–	–	–
No HWTT	0.0234	234	281	0.00999	100
Alum + chlorine	–	–	–	–	–

Note: Ps/Rs and Py/Ry denote the probability/range of infection risk per 10,000 exposed households with rainwater tanks from A single event and probability/range of infection risk per 10,000 exposed households per year in Ikorodu respectively.

possible that *E. coli* may not necessarily be present in the tank for the whole period (especially at the top of the storage tank due to sedimentation). By substituting $E = 281$ into Equations (3) and (4), the results in Table 4 can be estimated, which shows the maximum infection risk for individuals exposed to contaminated tank water for all investigated HWTT scenarios. The results showed that for 10,000 households, the maximum risk is 96 and 100 for those who apply alum and no HWTT respectively. This further reinforces the need for a disinfectant.

Public health impact of different scenarios in the Ikorodu area of Lagos

The analysis of the results in Table 3 showed that almost 25% of total households drink rainwater in Ikorodu, and 10.5% of total households are at risk of exposure due to *E. coli*. This estimate includes 7,741 households that apply only alum and the 6,645 households that apply no form of treatment before drinking the harvested rainwater (Table 3). In other words, among 34,252 households that harvest and drink rainwater in Ikorodu, 42% (14,386) of them are exposed to the pathogen risk.

In this study's analysis, it is recommended that alum users or those who do not apply any form of water sterilising technique should use either chlorine, boiling or the combination of chlorine and alum. The little to no risk potential exhibited by water treated with chlorine and boiling can be attributed to the processes of killing the existing bacteria, which alum alone is not able to do. However, the use of untreated RHRW can still be recommended for non-potable uses (such as farming and toilet uses), which is important since it has been identified that 91% of the respondents harvest and use RHRW for daily needs. Agreeing with this finding, a negligible low risk level of *E. coli* infection was reported by Ahmed *et al.* (2010) when the RHRW was used as non-potable water.

It is important to recognise that *E. coli* is a surrogate parameter and it is strongly associated with bacteria contamination, either as heterotrophic or as a faecal group. In some cases, *E. coli* can itself cause health issues, especially for immunosuppressed people. The study used the maximum value of the *E. coli* strains that are harmful (i.e. 7%); this may have overestimated the presented results but it presents a necessary conservative approach, in particular to study the bottom-line cases. Despite the assumption, QMRA is still one of the standard and common techniques employed to estimate the health risk of consuming water from any water resource.

DISCUSSION

The results from the questionnaire showed a high dependency on rainwater as 114 respondent households (out of 125) harvested and used RHRW in the rainy season. The use of the RHRW varies from drinking to other domestic uses. The results showed that 31 of 114 rainwater harvesters drank the rainwater. Also, the survey found that 17 of the 31 respondents who harvested and consumed rainwater boiled it before drinking while only one applied chlorine. In comparison, the remaining seven respondents applied only alum which is not a disinfectant but a coagulant. This information was expanded to the Ikorodu population, where the QMRA results showed that for 10,000 households, the maximum risk is 96 and 100 for those who apply alum and no

HWTT respectively. The burden levels from the different scenarios in Table 2 significantly exceeded the WHO reference level except for disinfected water.

According to the study conducted by Ahmed *et al.* (2010), who used QMRA to evaluate the health risk from using RHRW in Australia, the percentage of the viable and harmful *E. coli* is (in most cases) within the range of 0–7%. Other studies by Machdar *et al.* (2013) stated that 8% of all *E. coli* are pathogenic. Comparatively, this study used a 7% estimate for viable and harmful *E. coli* to present a necessary worst-case approach. The study conducted by Ahmed *et al.* (2010) also showed the risk of infection from consuming untreated rainwater which contains *Gardia lambia* and *Salmonella* spp. The estimated maximum risk per 10,000 persons per year for *Gardia lambia* and *Salmonella* spp. are 65 and 54 respectively. Another QMRA study assessed the health risk of drinking RHRW which contains *Campylobacter*, the results gave 3.4 per 10,000 persons per year; while the risk of infection from toilet flushing, washing, irrigation and bathing are all negligible (Hora *et al.* 2018). A comparison of the results from current and previous studies showed different levels of risk burden from various pathogens; however, it was found that *E. coli* can be regarded as a prime option for estimating the worst-case scenario due to it presenting higher probability to give a larger risk number.

Furthermore, this pilot QMRA study in Ikorodu recommends the use of RHRW with the application of at least one form of disinfectant. The methods suggested in this study include boiling and chlorination-based approaches. The cost of applying chlorination and boiling could be high in the studied rural area, but nonetheless the methods are imperative to reduce the risk of exposure. Also, it is important that more research on the long-term public health risk associated with rainwater consumption is conducted in this study area.

CONCLUSION

In this paper, the health risk from the uses of RHRW in the Ikorodu area of Lagos, Nigeria using the QMRA process was investigated. The study also involved the use of results from survey questionnaires conducted in the study area. Data from the surveying of 125 households showed that rainwater was one of the major sources of drinking water in the rainy season, even though it may be exposed to pollutants, microbes, heavy metals, or toxic matter. Approximately 25% of the total respondents consumed rainwater. Most of the people who drank rainwater applied one form of the discussed HWTT treatments (including chlorine, boiling or the combination of chlorine and alum treatments); however, some still drank rainwater without any treatment. The risk caused by the consumption of RHRW was further evaluated using the guidelines for drinking water quality. Based on 2 L of ingestion a day and an average of 281 rainy days, the results revealed that the pathogenic *E. coli* exposure risk from the consumption of RHRW without application of any HWTT and with application of alum only were 100 and 96 respectively per 10,000 exposed households per year, showing the importance of applying disinfectant to the harvested rainwater before use.

This QMRA research represents a pilot study at Ikorodu to evaluate the potential and scale of pathogen exposure risk, and to raise awareness within the affected community. The results from this study can provide a useful insight into the possibility of QMRA utilisation at any other similar under-developed community who suffer from rainwater contamination.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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