Impacts of sedimentation on rainwater quality: case study at Ikorodu of Lagos, Nigeria

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

ABSTRACT

This study investigated the impact of sedimentation on rainwater storage system using a case study at the Ikorodu area of Lagos state, a rural area in Nigeria. In this investigation, the proportions of *Escherichia coli* (*E. coli*) that were settleable (due to sedimentation) and those that were at the free phase have been studied. Water samples were collected from different depths in the inspected rainwater storage tank at two different periods (i.e. rainy and dry periods) for 20 days. The samples collected from these periods have been analysed for physical and microbial measures before passing it through the serial filters with pore sizes of 500 μm, 100 μm, 10 μm and 1.5 μm to measure the retained particle mass. From the results, it was observed that: (1) the water quality at the free-phase zone was better than that at the tank's bottom; (2) the settleable bacteria rapidly sank to bottom; (3) the correlation of turbidity, *E. coli* and total suspended solids (TSS) for all the rain events showed a relatively high Pearson's coefficient of 0.9 to one another; and (4) over 70% of settling TSS occurred within first 36 h. Finally, it has been found that the physical sedimentation process can significantly reduce the microbial measures.

Key words | *Escherichia coli* (*E. coli*), rainwater, sedimentation, total suspended solids (TSS), turbidity

Chukwuemeka Kingsley John
Jaan H. Pu (corresponding author)
Faculty of Engineering and Informatics,
University of Bradford,
Bradford DB7 1DP,
UK
E-mail: *j.h.pu1@bradford.ac.uk*

Manish Pandey
National Institute of Technology (NIT),
Warangal, Telangana 506004,
India

Rodrigo Moruzzi
UNESP – Univ Estadual Paulista, Instituto de Geociências e Ciências Exatas,
Rio Claro,
São Paulo,
Brazil

HIGHLIGHTS

- It consists of a case study of roof-harvested rainwater at Ikorodu area of Lagos, Nigeria.
- In this study, sedimentation analysis has been used to quantify the rainwater quality (including its physico-chemical and microbial parameters).
- This paper presents a pilot rainwater quality study at the investigated area.

INTRODUCTION

The availability of fresh-water is under threat from several factors including pollution and climate change. Hence, it is important to invest in research and technology that will safeguard the availability of fresh-water. The findings from the literature have revealed that the pollutants from natural flows with unpredictable channel condition (Pu *et al.* 2016, 2020; Pu 2019), and from erosion sources along the natural channel beds (Pu *et al.* 2011, 2017; Pu 2021), can threaten the fresh-water sources.

Rainwater harvesting is a simple and sustainable way for obtaining fresh-water. There are two key benefits to using treated rainwater: (i) decreasing the pressure on the principal sources of water supply and (ii) providing a substitute source during periods of water scarcity. Regardless of these benefits, harvested rainwater has not been extensively used for ingestion due to a dearth of knowledge on the

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occurrence and hazard from the physical, chemical and microbiological contaminants (Ahmed *et al.* 2011, 2012).

Sedimentation is one of the processes used to improve the water quality, and it allows particles in water to settle under gravity. Studies have shown that sedimentation process can be aided by adding coagulants, such as aluminium sulfate (alum), that act to neutralise the negative electrical charge on particles and destabilise the forces to keep colloids apart (Zhou *et al.* 2012; Hussain *et al.* 2014). This study aims to investigate the impact of sedimentation on total suspended solids (TSS), turbidity and *Escherichia coli* (*E. coli*) at varying depths and periods at the rainwater storage tank at Ikorodu area of Lagos state, Nigeria. This study's experiments analyse the settling of *E. coli* and TSS in storage tank under their flocculation nature.

Studies by Krometis *et al.* (2013) and Characklis *et al.* (2005) reported that microbes (such as viruses, bacteria and protozoa) can be attached to solids in suspension that has unpredictable transport nature (Pu *et al.* 2021), thus the presence of suspended solids accommodates microbial contamination. In addition, elevated amounts of turbidity can shield microorganisms from the impacts of chlorination and stimulate the growth of bacteria, thus leading to a rise of chlorine demand in water treatment (Sharma & Bhattacharya 2017). In a water storage tank, the free phase bacteria can be killed by boiling or application of disinfectants since they are free floating in the water; while the sessile bacteria can be significantly reduced via the separation process of sedimentation (Olson *et al.* 2002; Characklis *et al.* 2005; Krometis *et al.* 2013). In this study, the level of settleable particles in the rainwater storage tank will be studied, and its correlation with the measured parameters (i.e. physico-chemical and microbial parameters) over varying depths and periods for different rain events will be investigated to draw necessary correlation between sedimentation process and water quality.

MATERIALS AND METHODS

Fractionation of samples by serial filtration

Fractionation of samples, which is a process of separating different sizes of particulate matter into smaller quantities by using serial filters, is used in this study. This method prepares sub-samples of suspended particulate matter within a given size range for subsequent gravimetric and microbiological analysis. Its concept has been presented schematically by the flowchart at Figure 1(a). Based on the initial sample of 4 L, the volume of 2 L of raw-water was separated for further analysis after gently shaking to provide a homogeneous solution. Initially, the raw-water was analysed for *E. coli* and passed through the 1.5 μm pore size filter. The standard method was used to obtain the weight of the deposit and its enumerated bacterial count in the raw sample. The remaining 2 L of the water sample was then passed through the 500 μm pore size mesh filter. The weight of the 500 μm pore size filter was measured before and after the passing of water sample to determine the mass of retained deposit. Subsequently, 100 mL of the filtrate was separated for microbiological analysis. The remaining filtrate from the 500 μm was then passed through 100 μm. Finally, the water was passed through the 10 μm pore size filter, and the filtrate was then analysed for microbes. In the separate measure, the 1.5 μm filter was used to estimate TSS present in the raw sample while other filter sizes gave a range of the solid mass deposited.

Physico-chemical parameters

The measured physico-chemical parameters include the Total Suspended Solids (TSS), turbidity, conductivity and pH. TSS were determined using the vacuum filtration device which has been suggested in other studies (Mendez *et al.* 2011; Olowoyo 2011; Olaoye & Olaniyan 2012). The turbidity of the water samples was further determined using Hanna Turbidimeter. The pH of water samples was analysed using PHS-3D pH meter, while conductivity was measured using electrical conductivity meter. The procedures used to determine these parameters are as described by the standard methods in APHA AWWA & WEF (2005).

Sedimentation and microbial measurements

A gutter and storage vessel were fixed to the building to allow rainwater to be harvested from the roof during rain events in our field data collection. The gutter has a length of 2.5 m and collects rainwater from the roof. The chosen storage vessel

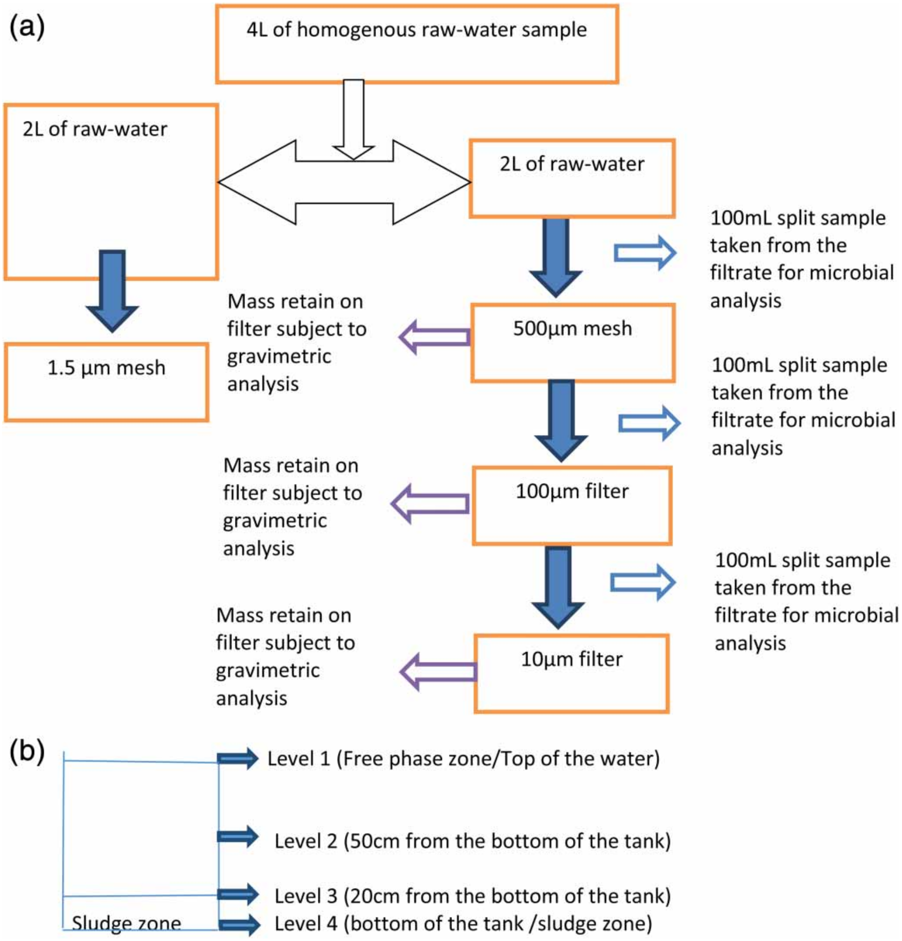

Figure 1 | (a) Experimental procedures for serial filtration and (b) various positions for water removal in the storage tank.

has a size of 255 L (diameter, ø = 60 cm, height, H = 90 cm) and made of plastic with a tight-fitting lid. The storage vessel was closed all the time except during the collection of water samples as to prevent external contaminant from entering. Water was collected at multiple depths, i.e. at the top of the tank by gently dipping a pre-sterilized bottle into the storage vessel, and at the bottom of the storage vessel via a siphon pump. Water samples were further collected from intermediate levels by installing small taps at depths shown in Figure 1(b). A small rigid pipe of 8 cm was attached to the inside of each tap to collect water samples from within the storage vessel. The storage tank was emptied and washed with sterilised water after each rain event.

All the storage vessel, gutter, PVC pipes and plastic bottles (that were used to collect the roof-harvested rainwater) were pre-washed with sterilised water to prevent external contamination. Furthermore, the sterilised water was analysed for microbes and the results showed that it was free of microbes (i.e. total coliform and *E. coli* were not detected). The collected water samples were stored in a cooler of ice and taken to the laboratory for analysis within 6 h of collection. After the analysis of each rain event, the remaining water in the vessel was discarded and the vessel was washed with sterilised water before use for the new harvested rainwater.

Water samples taken at each level were subjected to analysis of suspended solids and microbes in fractionated and unfractionated samples. The sampling program is summarised in Table 1. The values of turbidity, pH and conductivity were measured from the time of cessation of a rain event until the 20th day. The unfractionated solids and coliform bacteria were analysed on the 0th, 72nd, 168th,

Table 1 | Program of samples to be taken at each depth

Time since cessation of rainfall event (hours)	Turbidity, pH & conductivity	Suspended solid (fractionated)	Suspended solids (unfractionated)	Coliform bacteria (fractionated)	Coliform bacteria (unfractionated)
0	X		X		X
2	X	X		X	
4	X				
6	X				
8	X	X		X	
10	X				
12	X				
24	X				
36	X	X		X	
48	X				
72	X		X		X
96	X				
120	X				
168	X		X		X
240	X		X		X
360	X				
480	X		X		X
Total	17	3	5	3	5

240th and 480th hours; while the fractionated solids and coliform bacteria were analysed for the 2nd, 8th and 36th hours after the end of a rain event (Table 1). Four rainfall events were harvested and analysed for our sedimentation experiment. Within these events, one was in the dry season and the remaining three were in the rainy season.

The *E. coli* and total coliform concentrations were enumerated using the standard Colilert-2000® procedure (IDEXX, Westbrook, Maine, USA). The Colilert technique was executed in accordance to the manufacturer's guidelines (i.e. APHA protocol number 9223 B. Enzyme substrate test). All microbial testing in this paper was done in duplicate. Other studies that have also employed this duplicate method include Chao *et al.* (2003), Buckalew *et al.* (2006), Julian *et al.* (2015), Martin & Gentry (2016) and Tiwari *et al.* (2016).

STUDY AREA

The chosen area for this study is the Ikorodu Local Government Area of Lagos, Nigeria. This area has been selected for its inhabitant's dependency on rainwater harvesting, especially during the rainy season (Longe *et al.* 2010; Ukabiala *et al.* 2010), in which some of its residents even consume rainwater. Nigeria is situated in West Africa between latitude 4° and 14° North of the Equator, and between longitude 2° 2′ and 14° 30′ East of the Greenwich meridian. It is bordered by the Republic of Niger and Chad (at the north), by the Atlantic Ocean (to the south), by the Republic of Benin (to the west), and by the Republic of Cameroon (to the east). The climate of Nigeria varies from equatorial in the south to tropical in the centre, and to arid in the north. Nigeria's climate impacts the quantity and quality of the country's water resources. This occurs because of two main wind systems: the hot, dry, dusty wind which drifts from the northeast over the Sahara Desert and the relatively cool, moist, monsoon wind which drifts from the southwest over the Atlantic Ocean towards the country. The annual rainfall in Nigeria varies from 250 mm in the north to over 4,000 mm in the south, with a national average of 1,180 mm. Rainfall in Nigeria is seasonal, with the rainy season ranging from April to

September/October and the dry season ranging from November to March. The annual mean temperature is around 26 and 31 °C (78 and 88 °F) (Carter & Alhassan 1998; Alagbe 2002).

RESULTS AND DISCUSSION

Physico-chemical parameters from sedimentation experiments

The characteristics of the four investigated rain events are shown in Table 2. From the results at Table 3, the quality of roof-harvested rainwater was poorer than the free-fall harvested rainwater (used as benchmarked comparison). This is attributed to the roof as being one of the main sources of rainwater contamination. The quality of roof-harvested rainwater can be improved by regular cleaning of the roof before rain events especially after the long dry antecedent period. This study also showed that the water temperature at different levels of the storage vessel were similar.

Table 2 | Rain event characteristics

Harvest events	Total storm depth (mm)	Dry antecedent period (days)	Rainfall intensity (mm/h)
1	24.6	13	26.2
2	16.4	3	12.8
3	19.1	8	21.4
4	17.5	5	19.3

pH

The World Health Organization (WHO) recommends a guideline limit for pH between 6.5 and 8.5 for drinking water (WHO 2011). The results from the series of tests showed a similar trend in terms of pH for four levels of the storage vessel (Figure 2). The figure further showed that the pH value remained almost constant for the first day in all four levels. After the first day, the pH values increased in the top levels (1 and 2); while decreased in levels 3 and 4 (each level's description refer to Figure 1(b)). The pH changes in these levels can be caused by levels 1 and 2 being more aerated than levels 3 and 4. As observed, the pH did not fall within the range of the WHO guideline for drinking water. The pH of the first harvest (i.e. from the dry season) is higher than the other harvests (i.e. from the rainy season). This implies that there is higher accumulation of solids in the atmosphere during dry season. These acidity and alkalinity values can influence the quality of water over time. The pH value finding from our experiments has also been supported by previous rainwater studies which specified that the pH of most rainwater collected around the world is about 5.6 (Efe 2010; Olowoyo 2011; Chukwuma *et al.* 2012; Olaoye & Olaniyan 2012; Junaid & Agina 2014).

Table 3 | Quality of free-fall and roof-harvested rainwater for the four different harvest events

	1		2		3		4	
Parameters	**FFRW**	**RHRW**	**FFRW**	**RHRW**	**FFRW**	**RHRW**	**FFRW**	**RHRW**
TC (MPN/100 mL)	27.1	83.1	5.3	19.2	13.7	38.4	11.1	34.4
EC (MPN/100 mL)	5.3	22.2	1	6.4	4.2	12.4	3.1	8.7
Turbidity (NTU)	12	78	3.2	19.2	5.8	68.3	5.7	61.9
pH	5.9	6.4	5.3	5.6	5.6	5.7	5.6	5.9
Conductivity (μS/cm)	43	27	26	63	53	164	68	179
Colour (PCU)	10	65	5	15	10	60	5	35
TDS (mg/L)	28	43	18	38	19	61	18	64
TSS (mg/L)	51	182	28	85	49	187	42	196

Note: FFRW and RHRW denote Free-fall harvested rainwater and Roof-harvested rainwater respectively, while 1, 2, 3 and 4 represent the four different rain harvests as described at Table 2. This RHRW sample was collected directly from the roof to a sterilised plastic bottle.

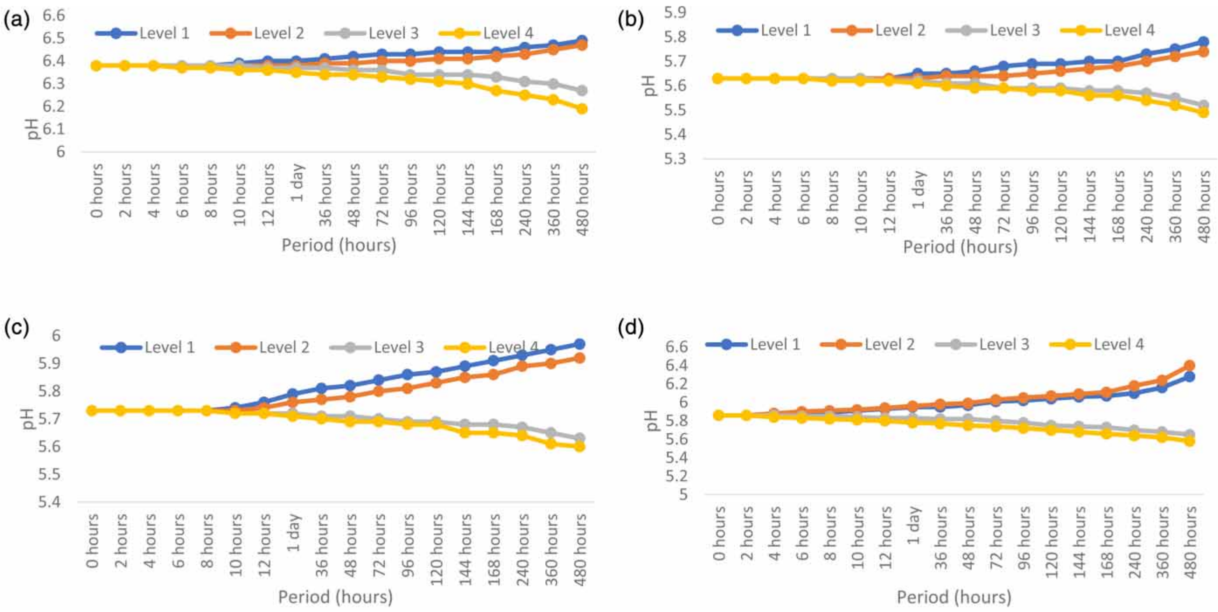

Figure 2 | pH values at different levels in the storage tank for (a) 1st harvest, (b) 2nd harvest, (c) 3rd harvest, and (d) 4th harvest.

The acidity in the harvested rainwater in the studied area was caused by the reaction of rainwater with the atmospheric acid which was deposited from many activities, such as agricultural activities, industries, dusts from unpaved roads, un-vegetative areas, and exhaust fumes from vehicles.

Conductivity

The results from Figure 3 evidenced that the conductivity values of the harvested rainwater have not exceeded the WHO guideline limits of 1,400 µS/cm (WHO 2011). There was continuous increase in the conductivity

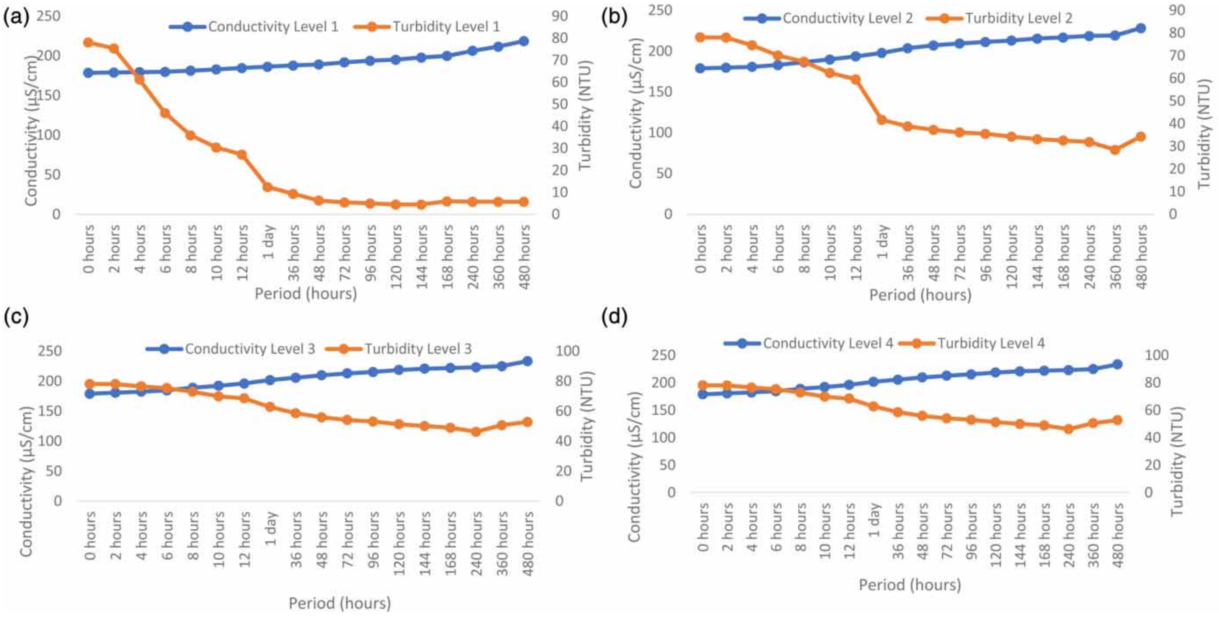

Figure 3 | Conductivity and turbidity values at different levels in the storage tank for (a) 1st harvest, (b) 2nd harvest, (c) 3rd harvest, and (d) 4th harvest.

values of the stored rainwater at different levels in the storage tank from the cessation of the rain until the 20th day for the four different harvests. However, the results showed that the rate of increment of the conductivity values was highest at level 4 and lowest at level 1, where the highest conductivity values in bottom level 4 was a result from the increment of the total dissolved solids (TDS) at that level.

Turbidity

The WHO guideline for turbidity in drinking water is 5 NTU and the obtained results showed that all the turbidity values for the harvested rainwater exceeded this limit (Figure 3). Although the major health impact of turbidity is not immediate, there are long-term impacts. For levels 1, 2 and 3 at the storage tank, this study's observation presented continuous reduction in the turbidity values (with over 50% of the reduction occurring within the first 24 h of harvest). This reduction in the turbidity values in top three levels resulted from the settling of particles in the storage vessel. Consequently, the turbidity value for level 4 evidenced continuous increase from the start of the experiment and was attributed to the settle-able particles from the top of the vessel.

Unfractionated total suspended solids (TSS) for different periods

This section describes the values of the TSS for the stored rainwater in the storage vessel for 20 days (Figure 4). A decrease in TSS values for the top three levels in the storage vessel and a continuous increase in the TSS values in the bottom level of the vessel was observed. Also it was seen that over 80% of sedimentation occurred within the first three days from the cessation of the rain, while the least settling of the particles occurred in the last two days. All the experimental results from the four rain events showed similar patterns.

Fractionated total suspended solids (TSS)

The size range of suspended solids from four varying depths in the storage vessel has been investigated as shown on Figure 5. The results from all rain events consistently showed a decrease of TSS in the top three levels of the

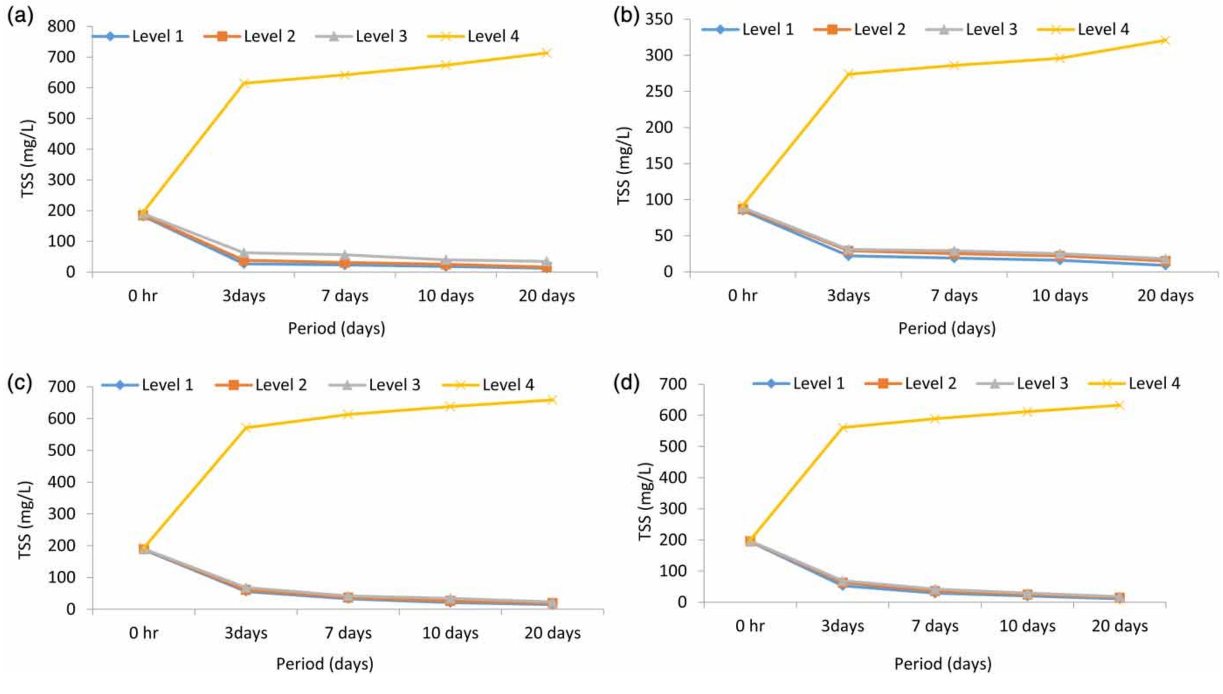

Figure 4 | Unfractionated total suspended solids (mg/L) for different periods for (a) 1st harvest, (b) 2nd harvest, (c) 3rd harvest, and (d) 4th harvest.

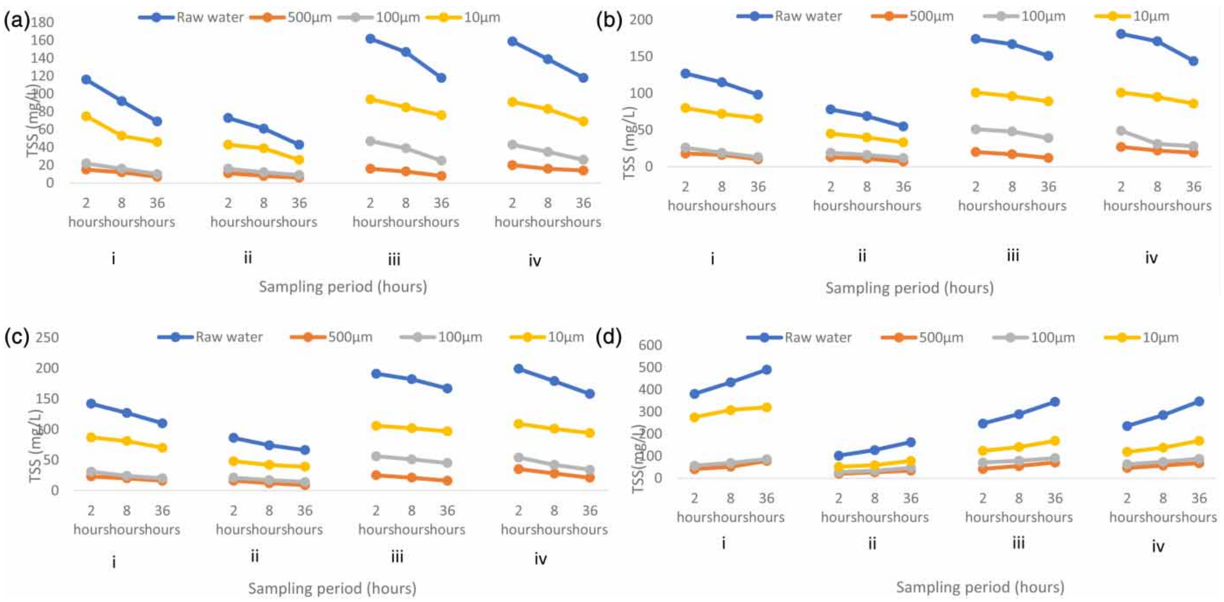

Figure 5 | Fractionated total suspended solids in (a) Level 1, (b) Level 2, (c) Level 3, and (d) Level 4 of the storage tank, and (i), (ii), (iii) and (iv) represent 1st, 2nd, 3rd and 4th harvest respectively.

storage vessel while an increase at the bottom, due to TSS settling. The results in Table 4 from the fractionation of samples showed that the percentage of solids (from the first rain event) retained in the 500 µm mesh filter during three different periods (i.e. 2 h, 8 h and 36 h) in the four levels ranged from 10.1% to 16.2%; whereas the percentage retained by 10 µm filter ranged from 57.6% to 72.2%. In comparison, during the second rain event, the TSS deposited in the 500 µm mesh filter in the four levels ranged from 12.7% to 21.3%; while the percentage retained by 10 µm filter ranged from 47.8% to 63.9%. Similar trends were observed for the third and fourth rain events.

Table 4 | Percentage of particles retained in the four levels at different periods for four rain events

		2 hours				**8 hours**				**36 hours**			
		Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
1st rain event	500 µm	12.9	14.2	16.2	10.8	13	13.9	15.7	12	10.1	10.2	14.5	15.9
	100 µm	19	20.5	14.8	15	17.4	16.5	18.9	15.9	14.5	13.3	18.2	17.6
	10 µm	64.7	63	61.3	72.2	57.6	62.6	63.8	71.1	66.7	67.3	63.6	65.3
	< 10 µm	3.4	2.3	7.7	2	12	7	1.6	1	8.7	9.2	3.7	1.2
2nd rain event	500 µm	15.1	16.7	18.6	19.6	13.1	15.9	16.2	21.3	14	12.7	13.6	20.9
	100 µm	21.9	24.3	24.4	26.5	19.7	23.1	23	26.8	20.9	21.8	21.2	28.8
	10 µm	58.9	57.7	55.8	51	63.9	58	56.8	47.9	60.4	60	59.2	47.8
	< 10 µm	4.1	1.3	1.2	2.9	3.3	3	4	4	4.7	5.5	6	2.5
3rd rain event	500 µm	12.6	14.9	17.6	19.5	11.5	12.9	15.6	20	11.9	13.2	13.3	19.6
	100 µm	27	27.1	27.1	26.7	25.2	18.1	23.5	26	21.2	19.4	21.5	25.4
	10 µm	57.2	55.8	54.8	50.4	59.7	55.6	56.4	48.4	58.5	59.7	59.5	48.7
	< 10 µm	3.2	2.2	0.5	3.4	3.6	13.4	4.5	5.6	8.4	7.7	5.7	6.3
4th rain event	500 µm	9.9	11.5	13.1	17	8.8	10.2	11.5	19	6.8	7.9	9.6	20.6
	100 µm	29	29.3	29.3	28.7	26.5	28.7	28	27.3	21.2	25.8	26.4	26.4
	10 µm	58	58	55.5	50.2	57.8	57.5	56	48.9	64.4	58.9	58.1	49
	< 10 µm	3.1	1.2	2.1	4.1	6.9	3.6	4.5	4.8	7.6	7.4	5.9	4

Figure 6 further describes the calculated settling velocities for the four levels in the storage tank at different periods 2, 8, 36, 72, 168, 240, and 480 (hours). The results evidenced that the minimum and peak particle settling velocities were obtained at level 4 and 1 respectively. The settling rate of particles in a storage tank is dependent on the depth of tank and the size of particles present. Conclusively from Figure 4, when water samples were considered unfractionated, it can be seen that over 70% settlement of TSS was observed within a period of 36 h.

Microbial parameters from the sedimentation experiments

The enumerated *E. coli* obtained from the analysis of roof-harvested rainwater, and the results from the serial filtration of the enumerated bacteria have been discussed here. The *E. coli* analysis at Table 5 showed that the quality of the stored rainwater is generally poor for consumption as it exceeded the WHO permitted amount for drinking water (0MPN/100 mL).

Unfractionated *E. coli* bacteria for different periods

Figure 7 presents the plots of the enumerated *E. coli* for the four rain events until the 20th day. Results showed that over 50% of *E. coli* settled from the top level of the storage tank over first three days, and at the same time, continuous increase in *E. coli* was observed at the bottom for all four rain events. This was an outcome from the settling of bacteria which are attached to the particles. It was also observed that *E. coli* values increased in level 1 during the 10th to 20th day, especially in the first and second rain event (Figure 7). This can be attributed to the bacteria regrowth which occurred because of viable environment. From the study conducted by Hill (2006) to investigate the bacterial activity in harvested rainwater, it can be concluded that the bacteria regrowth in the rainwater storage tank was due to the availability of sufficient nutrient substrate. Other factors which may lead to bacteria regrowth include the presence of organic matter, sufficient time for the bacteria to multiply, water temperature and chemical composition of water (Hill 2006). Hill's and current study have also been further supported by Adam & Kott (1989), Power & Nagy (1999), and Mahto & Goel (2008).

Fractionation of *E. coli*

Figure 8 present the results of the fractionated *E. coli* (in MPN/100 mL) for the harvested and stored rainwater from the four rain events; while Table 5 presents the percentage of particles retained in the four storage tank levels for all the rain events over the first 36 h of harvest. The finding showed a reduction in the enumerated *E. coli* in the top level

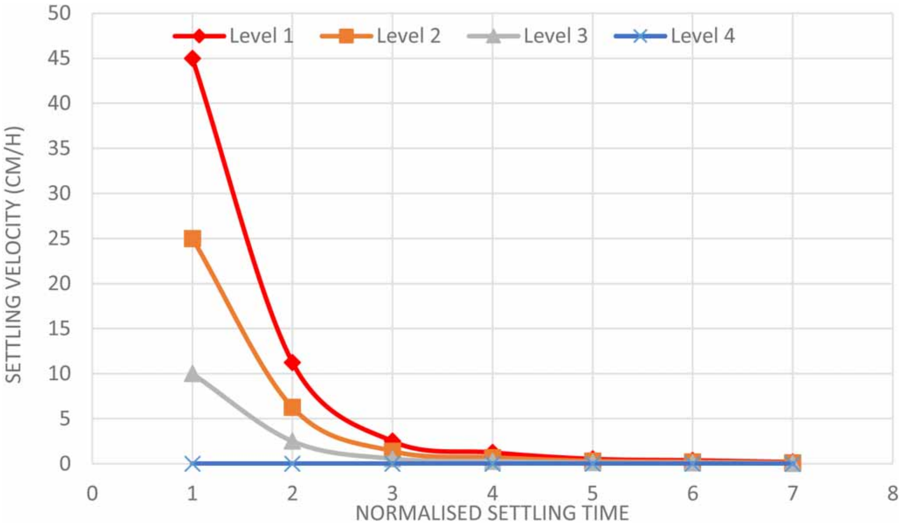

Figure 6 | Sedimentation velocity of the particles at different settling time periods (settling time 1–7 denotes 2, 8, 36, 72, 168, 240 and 480 h respectively).

Table 5 | Percentage of *E. coli* removed by different filter sizes for the four rain events

		2 hours				**8 hours**				**36 hours**			
		level 1	**level 2**	**level 3**	**level 4**	**level 1**	**level 2**	**level 3**	**level 4**	**level 1**	**level 2**	**level 3**	**level 4**
1st rain event	500 μm	7.2	0	0	0	7.3	6.8	6.7	5.9	8.5	6.7	6.3	11.1
	100 μm	13.5	13.5	6.7	5.9	7.3	6.8	6.3	5.6	7.9	12.6	12.2	10.5
	10 μm	19.3	6.3	6.3	11.5	14.1	6.3	6.3	5.6	15.9	11.8	11.4	4.9
	% removed	40	19.8	13	17.4	28.7	19.9	19.3	17.1	32.3	31.1	29.9	26.5
2nd rain event	500 μm	17.2	14.7	13.8	24.2	20.8	13.8	0	21.6	0	10.8	10.8	10.8
	100 μm	17.2	14.7	12.6	11.1	20.8	25.3	13.8	10.8	35.5	21.6	10.8	10.8
	10 μm	17.2	29.3	25.3	33.3	39.6	12.6	25.3	29.7	32.3	19.8	20.7	20.7
	% removed	51.6	58.7	51.7	68.6	81.2	51.7	39.1	62.1	67.8	52.2	42.3	42.3
3rd rain event	500 μm	10.8	10.5	9.5	8.7	12.1	9.5	8.7	7.9	14.7	8.7	7.9	7.2
	100 μm	21.6	9.7	9.5	17.3	23.2	9.5	8.7	15.2	14.7	8.7	15.2	13.5
	10 μm	19.8	19.4	17.5	8	22.2	17.5	16.7	14.6	29.3	16.7	14.6	13
	% removed	52.2	39.6	36.5	34	57.5	36.5	34.1	37.7	58.7	34.1	37.7	33.7
4th rain event	500 μm	0	14.7	0	0	0	0	12.1	0	0	10.8	0	0
	100 μm	29.3	14.7	14.7	13.8	17.2	13.8	12.1	12.1	28.6	10.8	10.5	10.5
	10 μm	29.3	44	29.3	37.9	51.6	37.9	22.2	23.2	47.6	20.7	29	29
	% removed	58.6	73.4	44	51.7	68.8	51.7	46.4	35.3	76.2	42.3	39.5	39.5

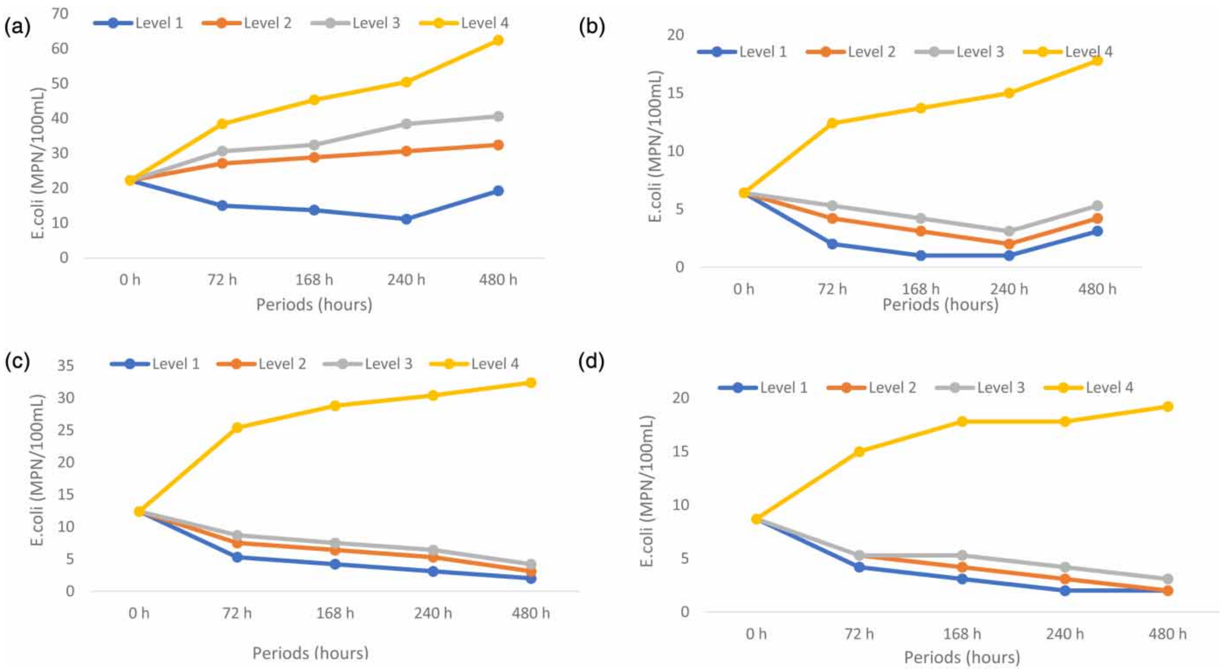

Figure 7 | Unfractionated *E. coli* (MPN/100 mL) in levels 1–4 for (a) 1st harvest, (b) 2nd harvest, (c) 3rd harvest, and (d) 4th harvest.

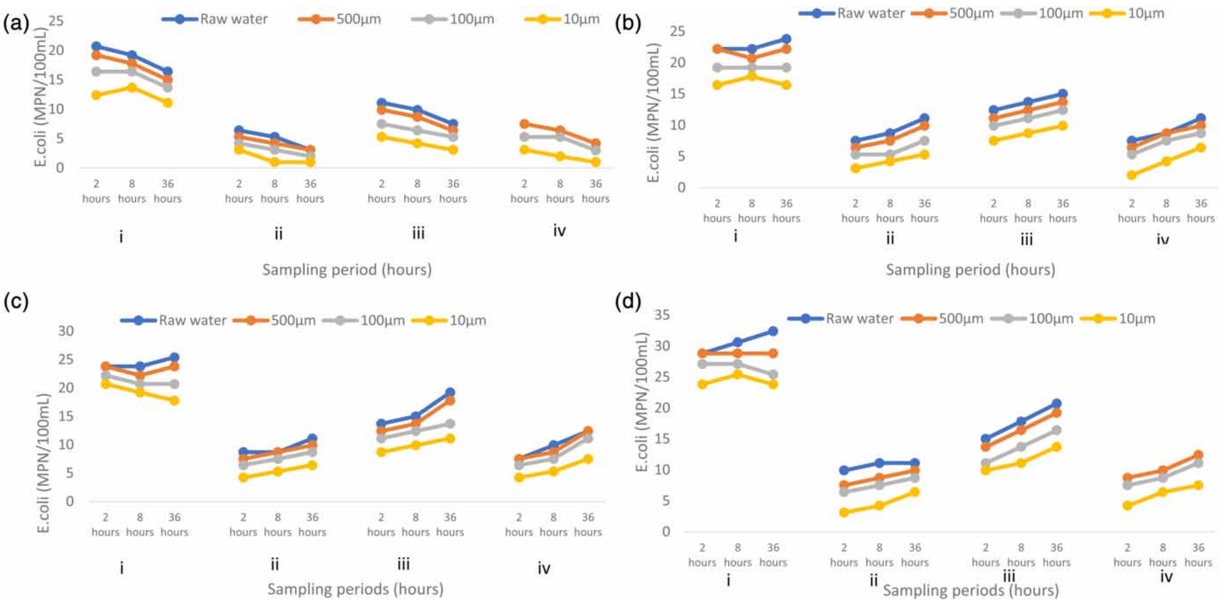

Figure 8 | Fractionated *E. coli* (MPN/100 mL) in (a) Level 1, (b) Level 2, (c) Level 3, and (d) Level 4 of the storage tank, and (i), (ii), (iii) and (iv) represent 1st, 2nd, 3rd and 4th harvest respectively.

of storage tank, accompanied by its continuous increase at the bottom three levels (Figure 8). The changes in the quantity of *E. coli* can be related to the settle-able particles in the storage tank. The results in Table 5 from the fractionation of samples showed that the percentage of *E. coli* (from the first rain event) retained in the 500 µm mesh filter during three different periods (2 h, 8 h and 36 h) in the four levels ranged from 0% to 11.1%; while the percentage retained by 10 µm filter ranged from 4.9% to 19.3%. On the other hand, the same analysis for the second rain event showed the TSS deposited in the 500 µm mesh filter in the four levels ranged from 0% to 24.2%; and the percentage retained by 10 µm filter ranged from 17.2% to 39.6%. This trend was also observed for the third and fourth rain events. The analysis of Table 5 also evidenced that little or no *E. coli* was removed by the 500 µm mesh filter; while comparatively large amount of *E. coli* were removed by the 10 µm filter.

It can be concluded that the retention of solids by the filters during the serial filtration led to the reduction in the enumerated *E. coli*. The analysis of results from our experiments showed that not all the *E. coli* in the raw samples were collected after the serial filtration. This can be caused by two reasons: (1) some bacteria being in a free phase (i.e. they are not attached to any solids) and (2) some of the solids being smaller than the 10 µm filter. The results also showed that the process of particle sedimentation in water storage systems improved the quality of harvested rainwater over time.

Statistical analysis of the parameters

The Pearson's correlation was further conducted using the unfractionated sample data of turbidity, TSS and *E. coli* over 0, 72, 168, 240 and 480 h. Table 6 presents turbidity versus *E. coli* correlation matrix between four storage levels in all four rain events across the five stated times. The results presented relatively high correlation across all levels for all rain events with the least (0.68) and peak (0.996) correlation observed in levels 3 and level 4 respectively. In agreement with this study, high correlation between turbidity and enumerated bacteria were also observed in several other studies (Irvine *et al.* 2002; Huey & Meyer 2010; Lawrence 2012). Table 7 further demonstrates correlation matrix between turbidity and solids (TSS) for all levels in all rain events across same period range (over five investigated times). The finding has consistently proven high correlation (minimum of 0.9) within all four levels, where similar conclusion was also proposed by previous studies (Draper & Smith 1981; Ferguson 1986;

Table 6 | Pearson's correlation between *E. coli* and turbidity for four rain events in four storage tank levels

		Level 1		Level 2		Level 3		Level 4	
		E. coli	Turbidity	*E. coli*	Turbidity	*E. coli*	Turbidity	*E. coli*	Turbidity
1st event	*E. coli*	1.00		1.00		1.00		1.00	
	Turbidity	0.75	1.00	0.88	1.00	0.83	1.00	0.98	1.00
2nd event	*E. coli*	1.00		1.00		1.00		1.00	
	Turbidity	0.92	1.00	0.84	1.00	0.68	1.00	0.97	1.00
3rd event	*E. coli*	1.00		1.00		1.00		1.00	
	Turbidity	0.97	1.00	0.91	1.00	0.91	1.00	1.00	1.00
4th event	*E. coli*	1.00		1.00		1.00		1.00	
	Turbidity	0.97	1.00	0.93	1.00	0.95	1.00	0.97	1.00

Table 7 | Pearson's correlation between turbidity and solids for four rain events in four storage tank levels

		Level 1		Level 2		Level 3		Level 4	
		Turbidity	Solids	Turbidity	Solids	Turbidity	Solids	Turbidity	Solids
1st event	Turbidity	1		1		1		1	
	Solids	0.997	1	0.9936	1	0.9678	1	0.9341	1
2nd event	Turbidity	1		1		1		1	
	Solids	0.988	1	0.9939	1	0.9996	1	0.9836	1
3rd event	Turbidity	1		1		1		1	
	Solids	0.991	1	0.9886	1	0.9975	1	0.9842	1
4th event	Turbidity	1		1		1		1	
	Solids	0.995	1	0.9947	1	0.9967	1	0.9995	1

Davies-Colley & Smith 2001; Embry 2001). Majority of the correlation values were over 90%, and these high correlations were the key evidences that a significant proportion of *E. coli* fraction is both settleable and attached to the TSS solids while settling.

CONCLUSIONS

This study has investigated the impact of sedimentation on the microbiological and physical measures over different periods and depths in the rainwater storage tank for different rain events at Ikorodu of Lagos, Nigeria. The change in the physical parameters in the tank showed there was rainwater quality improvement with time especially at the top two levels, while poorer quality was observed at the bottom of the tank. This occurrence was attributed to the settling of solids, where over 70% of the settlement occurred in the first 36 h. On the other hand, the change in the microbial parameters in the tank also proved that there was improvement in the quality of the top two levels, while deteriorated at the bottom with time. From the Pearson's correlation of turbidity versus *E. coli* and turbidity versus TSS, the process of sedimentation has been proven not only to reduce the TSS and turbidity, but also decreased bacteria at the top of the rainwater storage tank.

The analysis also revealed that the quality of the free-fall rainwater was better than the roof-harvested rainwater, and that was resulted from the roof being a pathway for contaminants to enter into the storage tank especially after long dry antecedent period. The recorded quality of both free-fall and roof-harvested rainwater remained poor and did not meet the WHO guideline for drinking water, which present a caution to the store rainwater drinking practice that exists in this part of Africa.

Based on the results of this study, it can be summarised that the physical sedimentation process can significantly reduce the microbial measures. Hence, it is recommended for the harvested water to be stored, in order for sedimentation phrase to take place. Also, it is important that the water consumption to be restricted to the top level of the storage tank only. Finally, proper hygiene such as regular cleaning of the storage tanks, pipes and gutters are important to help improve the quality of the harvested rainwater.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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