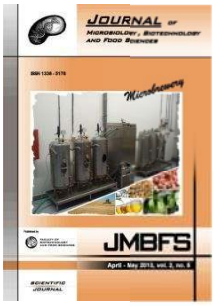

JMBFS
Journal of Microbiology, Biotechnology and Food Sciences
International peer-reviewed scientific online journal

Published by Faculty of Biotechnology and Food Sciences

Nzung'a et al. 2013 : 2 (5) 2294-2300

TECHNIQUES FOR POTABLE WATER TREATMENT USING APPROPRIATE LOW COST NATURAL MATERIALS IN THE TROPICS

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ARTICLE INFO

Received 24.10.2012
Revised 14.2.2013
Accepted 14.2.2013
Published 1.4.2013

Regular article

OPEN ACCESS

ABSTRACT

The effectiveness of mechanical filtration and solar irradiation in water treatment was evaluated. Selected metals and non-metals ions before and after treatment were determined colorimetrically while turbidity was measured using a turbidimeter. pH, electrical conductivity, dissolved oxygen (DO) and temperature were measured using a portable universal multiline P4 WTW meter while total alkalinity was determined titrimetrically. The load of coliform bacteria contamination before and after treatment was determined by Millipore filtration method. Screening for the presence of pathogenic bacteria was carried out using standard methods. The levels of the properties before and after treatment were each compared with the recommended drinking water standards according to Kenya Bureau of Standards (KEBS) and World Health Organization (WHO). The water was treated by being subjected to mechanical filtration and solar irradiation and changes in their physico-chemical properties and bacteriological load determined. The results obtained after treatment revealed that solar irradiation killed most of the pathogenic bacteria after exposure for eight hours but had no impact on the physico-chemical properties except nitrates (from 24.5 to 8.0 mg.L^{-1}). Mechanical filtration reduced total coliforms and *E. coli* by 30 %. It also reduced the loads of Zn, Cu, Mn, Pb, Fe, nitrate nitrogen and turbidity of the water treated to an almost potable state. Water treatment using a combination of mechanical filtration system and solar disinfection was found to be very effective in reducing the bacterial load.

Keywords: Mechanical filtration, solar irradiation, water treatment, physico-chemical properties, bacterial load

INTRODUCTION

Access to safe drinking water is an important component in prevention of waterborne diseases such as typhoid, shigellosis and cholera. One goal of the Millennium Declaration by the United Nations (UN) is to reduce by half the number of people without safe drinking water by the year 2015 (**UN, 2000**). Diarrhoeal diseases are some of the major causes of morbidity and mortality in developing countries (**Gasana *et al.*, 2002**). These diseases are responsible for approximately 2.5 million deaths annually in developing countries, affecting mostly children younger than five years, especially in areas with limited access to potable water supply and sanitation (**Kosek *et al.*, 2003; Lin *et al.*, 2004, Obi *et al.*, 2004**). Drinking water is the primary route of transmission of infectious diarrheal bacteria in rural areas (**Alamanos and Gessouli, 2000**). Tens of thousands of people, many of them children, die each year due to diarrhea, resulting from use of unsafe drinking water (**GOK, 2001; World Bank, 2004**). It is estimated that 60 % of the people in developing countries live without adequate supply of drinking water (**World Bank, 2004**). Studies have shown that worldwide over 3 billion people suffer from water related diseases as a consequence of using unsafe water and exposure to inadequate sanitation (**WHO, 1999**). Mortality and morbidity rates would be greatly reduced if access to safe drinking water were improved.

Potable water supply must be free from pathogens such as bacteria, viruses and protozoan parasites, dissolved toxins, meet the standard guidelines for turbidity, odour, colour, appearance, chemical concentrations and taste, and must be available in adequate quantities (**Kirkwood, 1998**). However, inadequate sanitation and persistent fecal contamination of water sources has contributed to the large percentage of people in both developed and developing countries that do not have access to microbiologically safe drinking water and hence exposed to diarrheal diseases (**WHO, 2002a & b**). According to the U.S. Environmental Protection Agency, 90% of the world's water is contaminated in some way (**Prescott, 2002**). The main sources of contamination in water supplies are pathogenic microbes, heavy metals, organic substances and inorganic chemicals. To reduce the potential health risk resulting from use of contaminated water, treatment methods are needed that are easy to use, effective, affordable, functional and sustainable (**Sosbey, 2002**). Water is treated to improve its utility for domestic and industrial purposes, to remove pathogenic and potentially pathogenic microorganisms, to decrease turbidity, to eliminate taste and odor, to reduce or eliminate nuisance chemicals such as iron and manganese and to soften it to make it more useful for laundry. There is no water purification method, which is 100% effective hence in every treatment one should always have at least one back up method in case the method in use fails (**Mackane and Kandel, 1996**).

Most cities in Africa lacks piped water and as a result of the low and erratic rainfall, poverty and low level of technology uptake, they experience frequent shortage of potable water. During periods of low water availability, competition for water between humans and livestock is common. The pressure of use combined with a diversity of users results in contamination of water sources. Human and animal wastes, which may get into water sources through surface run off, could contain pathogenic bacteria such as *Salmonella typhi, Shigella sp.*, *Vibrio cholerae, Clostridium perfringens, Escherichia coli* and protozoa like *Entamoeba hystolytica*. The majority of households use untreated water, which poses health risks due to waterborne diseases.

Although natural resources with the potential for water purification are readily available, no attempt has been made to utilize these resources in water treatment. This work therefore determined the effectiveness of a number of treatment options. Commercially used water treatment methods are too expensive to anyone living on less than a dollar a day. More so, chemical water treatment methods such as chlorination and use of iodine poses health risks and may not completely eliminate all pathogens (**Jensen *et al.*, 2003**). They also change the taste and color of water, which discourages people from using it for cooking and drinking. The objective of our study was to compare the effectiveness of selected water treatment methods commonly used in rural settings.

MATERIAL AND METHODS

Physical and chemical quality of water

Temperature **(^oC),** dissolved oxygen (μgL^{-1}) and pH was measured using probe of a portable WTW Multiline meter (Wilhelm, Germany). The probe was first lowered into the water and the meter readings allowed to stabilize for three minutes before the readings were taken as depicted by the in-built sensor. Total alkalinity ($mgCaCO_3\ L^{-1}$) was determined titrimetrically using standard hydrochloric acid and mixed bromocresol green-methyl red indicator to determine the titration end point (**APHA, 1998**). Turbidity (NTU) was determined by comparing the intensity of light scattered by the water sample to the intensity of light scattered by a standard reference in the turbidity meter. In this study, turbidity was determined by the turbidimetric method using a LaMotte turbidimeter (Model No. 2020) as outlined in the user's manual. Color (mg pt L^{-1}) was measured using colorimeter (LaMotte Smart Model No. 26632) following the platinum cobalt method as outlined in the user's manual.

Nitrate nitrogen, chlorides, fluorides, sulfates, calcium, zinc, copper, manganese, lead and iron in water samples were measured using colorimeter (LaMotte Smart Model No. 26632) as outlined in user's manual. The methods used were zinc reduction (code 3689-Sc), argentometric (code 3693), spadns (code 3647-01-Sc), barium chloride (code 3665-Sc), unit dose vials (UDV) (code 4309-H), zinc cyanide complex formation (Zincon), bicinchoninic acid (code 4314-H), PAN (1-2-Pyridylazo-2-Naphthol) (code 3658-01-SC), PAR(code 4031) and bipyridyl (code 3648-Sc) respectively.

Microbial characterization of water

Total coliform counts

Using a pre-sterilized membrane filtration apparatus, 100 mL of appropriately diluted water sample was filtered through 0.45 µm pore size sterile membrane filter pad and the filter placed face up on the Petri plate containing mEndo agar and incubated at 37 ^oC for 24 hours. The bacteria trapped in the membrane filter pad formed colonies, which were counted using a colony counter to obtain total bacteria per 100 mL. Selected colonies from the mEndo agar plates were sub cultured in duplicate brilliant green lactose bile fermentation broth tubes with a Durham tube inserted and incubated at 37^oC for 24 hours. A drop of culture from the positive lactose broth was streaked onto a nutrient agar slant and incubated at 37 ^oC for 24 hours. The colonies formed were then Gram stained. Coliforms are Gram-negative, non-spore-forming facultative anaerobic rod-shaped bacteria that ferment lactose to produce acid and gas within 48 hours at 35 ^oC (**Grant, 1997**).

Faecal coliform analysis

Analysis of water samples for faecal coliforms (thermotolerant coliforms) was by passing a 100 ml of water sample through a sterile Millipore filter pad and placing the Millipore filter pad after filtration onto a Petri-plate containing mEndo agar and incubated at 44.5 ± 0.2 ^oC. The purpose of incubating the Petri-plate at 44.5 ^oC in the Kit's incubator was to ensure that only thermotolerant coliform bacteria grew. During the time of incubation, the coliform bacteria multiply many times to form colonies that are visible with naked eyes. Faecal coliforms are Gram-negative, non-spore-forming, facultative anaerobic rod-shaped bacteria that ferment lactose to produce acid and gas within 48 hours at 44.5 ^oC (**Grant, 1997**). Thermotolerant coliforms are recognized by their ability to produce a colour change from red to yellow in the culture medium at 44.5 ^oC. The results obtained were expressed as colony forming units per 100 mL (CFU per 100 mL).

Screening for genus Salmonella and Shigella

A one millilitre water sample was enriched with Selenite F broth and incubated at 37^oC for 18 - 24 hours. A loopful of the broth was then carefully streaked on a Petri-plate containing Salmonella-Shigella agar and incubated at 37^oC for 18 - 24 hours. *Salmonella* colonies are colorless with black center while those of *Shigella* are colorless, shinny with no black center. Presence of genus *Salmonella* and *Shigella* were confirmed by transferring the suspected colonies onto triple sugar iron (TSI) agar. Further confirmatory tests were conducted by inoculating the colonies onto motility indole urease agar test using SIM media (CM435) and incubated at 37^oC for 18 - 24 hours. The culture was examined for motility and hydrogen sulphide production. The aim of this test was to differentiate between motile, urease positive hydrogen sulphide producing *Salmonella* and non-motile urease negative, non-hydrogen sulphide producing *Shigella* (**APHA, 1998**)

Screening for Vibrio cholerae

An amount of 0.1 mL of each water sample were enriched with alkaline peptone water broth in different tubes and incubated for 6 - 8 hours at 35^oC. A loopful of enriched broth was streaked onto Thiosulphate Citrate Bile Salts-sucrose (TCBS) agar plate and incubated at 35^oC for 18 - 24 hours. *Vibrio cholerae* colonies are yellow in colour, oxidase positive and 2 – 3 mm in diameter. A drop of overnight pure bacterial peptone culture was transferred onto the surface of oxidase discs. Positive results were indicated by immediate change of the disk from white to purple colour (**Cheesbrough, 1985**). The colonies were Gram stained to confirm the presence of *Vibrio cholerae*. *Vibrio cholerae* is characteristically Gram negative and comma or curve-shaped rods (**Downes and Ito, 2001**).

Screening for faecal Streptococci

Subcultures were made from colonies obtained in EMB agar into a tube containing 5 mL glucose azide broth and incubated for 18 hours at 37^oC. Positive results of *Enterococcus faecalis* were indicated by production of acid in the medium (**APHA, 1998**).

Screening for Clostridium perfringens

Colonies formed in EMB agar were inoculated in litmus milk medium and incubated at 37 °C for 5 days. Positive results of *Clostridium perfringens*, which are pathogenic Gram-positive bacteria, were indicated by a typical stormy clot reaction together with acid formation (**APHA, 1998**).

Screening for Klebsiella sp.

A 1 mL water sample was measured and appropriate dilutions done before membrane filtration. The membrane filter after filtration was placed on the surface of modified-FC agar and incubated for 24 ± 2 hours at 35 - 37°C (**APHA, 1995**). A minimum of 5 typical colonies were verified to ascertain whether they were of genus *Klebsiella* colonies by transferring a loopful of the colony to a commercial multi-test system for Gram-negative speciation (**APHA, 1998**).

Water treatment

Mechanical filtration unit that employed a sand filtration system

Typical sand filter systems were constructed in underground trenches and an above-ground sand filter using 100 and 20 litres containers. The containers were packed with charcoal, gravel and sand respectively and untreated water run through the system and collected as clean water as shown in figure 1.

Mechanical filtration units using a PVC U-shaped pipe

A single and double Polyvinyl chloride (PVC) U-shaped pipes were used in construction of filtration units by being filled with charcoal, gravel and sand respectively and unclean water allowed to pass through the column as shown in figure 2.

Contaminated water source based on its turbidity and bacterial load quality was chosen for the purification tests. The water samples were passed over different columns each of 0.15 m depth lined with charcoal, coarse gravel, fine gravel, coarse sand and fine sand. The grain size of the sand used ranged from 0.2 - 0.4 mm. The minimum depth of the whole system was 0.9 m. Day temperatures were between the ranges of 23 – 26 °C. Physico-chemical and bacteriological quality (counts of total and fecal coliforms) in each of the water sample was tested before filtering the water and after filtration to determine the changes associated with the treatment process. A 0.1 mL aliquot of bacterial suspension of *E. coli, Klebsiella* sp., *Salmonella* sp., *Vibrio cholerae*, *Clostridium* sp., *Streptococcus* and *Shigella* sp isolated from the most contaminated water sample was each mixed with 0.9 mL distilled water in a sterile glass test tube and incubated for 24 hours at 37 °C. The contents were then thoroughly mixed with one litre distilled water. The distilled water spiked with bacteria isolates was then passed through the sand filter and results recorded. The sand after filtration was autoclaved at 121 °C for 15 minutes before disposal to destroy the pathogenic microorganisms.

In mechanical filtration using PVC pipes, one portion of the water sample was passed through U-shaped PVC pipes with a diameter of 0.1 m and packed with layers of charcoal, gravel and sand, each occupying a depth of 0.36 m and set to achieve filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} respectively (figure 2). Another portion of the water sample was allowed to pass through a pair of U-shaped PVC pipes arranged in series, each with a diameter of 0.1 m and packed with layers of charcoal, gravel and sand of a similar depth as above (0.36 m deep each) but with filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} respectively (Figure 2).

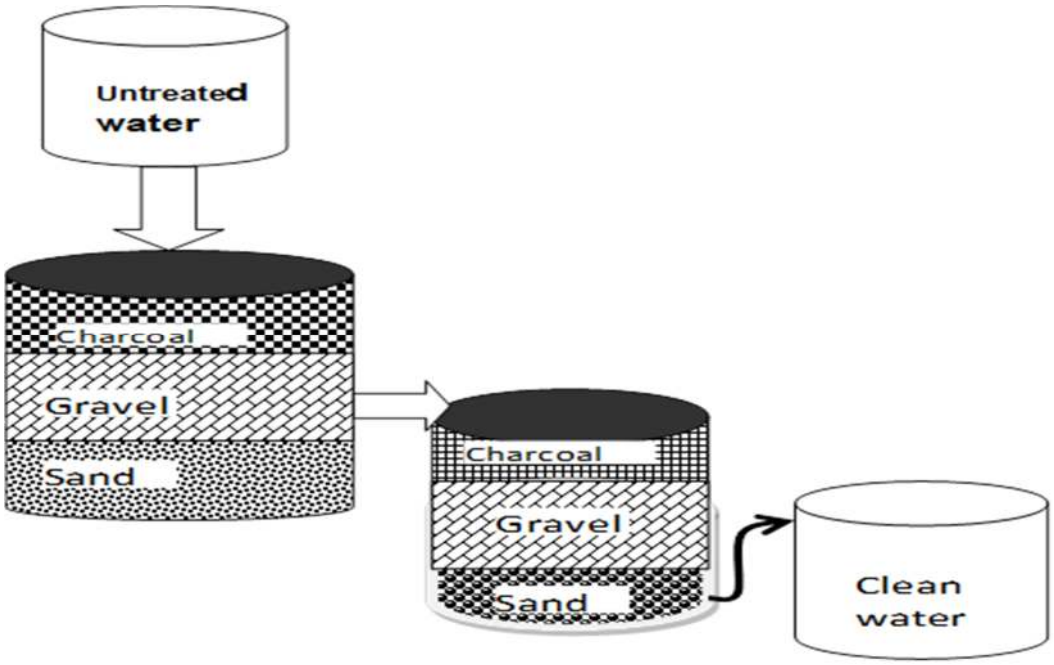

Figure 1 Mechanical filtration unit that employed a sand filtration system (The arrows show the direction of water flow)

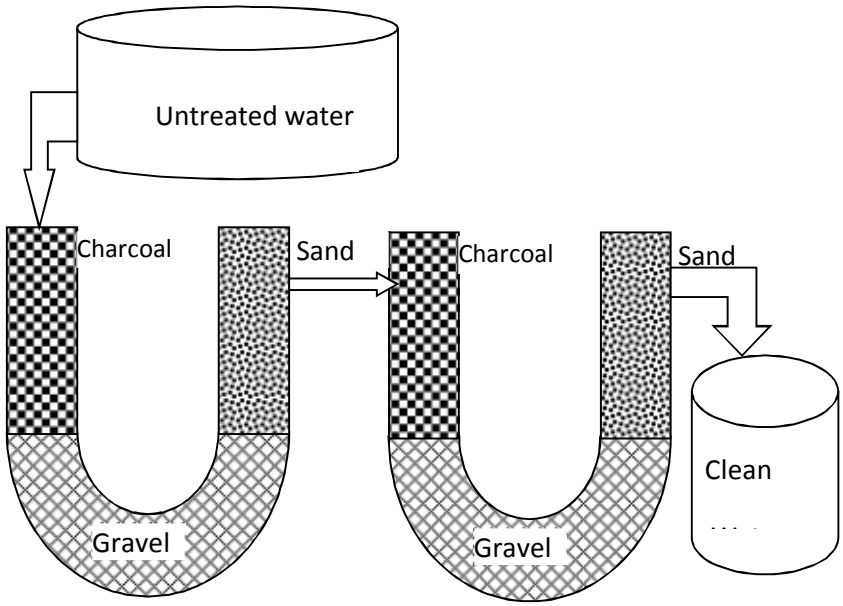

Figure 2 Mechanical filtration units using a single PVC U tube and a two PVC tubes arranged in series

Solar irradiations of water was carried out by exposing water samples in sterilized plastic bottles and plastic paper bags to direct sunshine for periods of up to eight hours. One portion of the water sample was placed in a sterilized one litre transparent plastic bottle used for packaging mineral water and kept in direct sunshine for six hours. One-half of the bottles were placed flat on a black polythene paper and placed on the ground while the other was placed on an iron sheet roof top. Another portion of the same water sample was subjected to the same treatment using transparent polythene paper bags instead of the transparent plastic bottles. In each treatment, the exposure to sunshine was from 10.00 am - 4.00 pm on days when no cloud cover or rainfall was expected. Each of the four treatments (plastic bottle on roof top, plastic bottle on black polythene paper, polythene paper on roof top, polythene paper on black polythene paper) were then analyzed for the reduction in bacterial load and turbidity.

Physico-chemical and microbial quality of the treated water were compared with **KEBS (1996)** and **WHO (2006)** water quality standards (Appendix I and II) to determine if individual treatment methods could meet the regulatory standards. Results of these comparisons were presented as the % of samples which exceeded the water quality standards.

Data analysis

The efficacy of the three treatment methods (sand filter, mechanical filtration and solar irradiation) was established on the basis of the reduction in bacterial load of the water samples.

RESULTS

Effects of solar disinfection on bacteriological quality

Total coliform counts of water samples disinfected through exposure to sunlight were recorded after periods of 1 hour, 2 hours, 4 hours and 6 hours respectively. The bacterial cells per 100ml were calculated by multiplying the number of colonies formed by the dilution factor. Total coliform counts in the water samples reduced from an initial count of 2.6875×10^4 CFU per 100 mL to 1.3×10^1 CFU per 100 mL after 1 hour of exposure. An exposure for a period of 6 hours resulted in samples free from total coliforms. After solar irradiation, the number of *E. coli* in water samples reduced from 3.9×10^3 to 1.0×10^1 CFU per 100 mL after 5 hours of exposure and after 6 hours of exposure, there were no *E. coli* detected in the water sample. Both the transparent plastic bottles (dasani) and

the transparent polythene papers had a similar effectiveness in reducing the total coliform load of tested water samples.

Exposure of contaminated water samples to sunlight in transparent plastic bottles on a black background at a temperature range of between 24 - 28 ^{o}C resulted in the elimination of *Salmonella* and Streptococci after 75 minutes of exposure. After two hours of exposure, *Shigella* was absent in the water samples. All pathogenic bacteria could not be detected after a continuous exposure for six hours. A continuous presence of *Salmonella, Shigella* and *Streptococcus* sp. in contaminated water samples kept indoors for at least 6 hours as control from 10.00 am - 5.00 pm at room temperature (23 - 25 ^{o}C) was recorded. Exposure of contaminated water to sunlight in transparent plastic bottles on top of house roof at a temperature range of 24 - 28 ^{o}C led to the elimination of *Clostridium perfringens* after 45 minutes. After 75 minutes, *Streptococcus* could not be detected while a continuous exposure for 90 minutes resulted in the absence of *Shigella* and *Klebsiella* in the water samples. *Vibrio cholerae* and *Salmonella* sp. could not be detected after three hours and four hours of exposure respectively. *E. coli* was found to be present even after five hours of exposure. After six hours it was found to be below the limit of detection. Therefore its persistence in water during treatment in comparison to *Salmonella, Klebsiella, Clostridium, Vibrio cholera* and *Shigella* was sufficient enough to be used as an indicator microorganism for human pollution and completion of solar irradiation.

Continuous exposure of contaminated water samples to sunlight for a period of six hours in transparent water bottles led to a reduction in total coliforms colony counts from 2.6875×10^4 bacteria per 100 mL to 1.3×10^1, seven, two and zero bacteria per 100 mL after one, two, four and six hours respectively while the *E. coli* reduced from 3.9×10^3 CFU per 100 mL to ten, five, three and zero per 100 mL after one, two, four and six hours of exposure respectively. Another water sample exposure to sunlight using transparent polythene papers over a period of six hours resulted in a reduction in total coliform counts from 2.6875×10^4 CFU per 100 mL to twelve, five, one and zero CFU per 100 mL after one, two, four and six hours of exposure respectively while the *E. coli* reduced from 3.9×10^3 CFU per 100 mL to nine, five, three and zero CFU per 100 mL after one, two, four and six hours of exposure respectively. Control water samples kept indoors over a six hours period in transparent water bottles did not show any appreciable change in colony counts of total coliforms and *E. coli*. Total coliforms counts reduced from 2.7325×10^4 to 2.7256×10^4 CFU per 100 mL while *E. coli* reduced from 3.4×10^3 to 3.383×10^3 CFU per 100 mL.

Effects of solar irradiations on physico-chemical properties of the water

Sample exposure to sunlight resulted in changes in some of the physico-chemical properties of the water. Levels of nitrate nitrogen in water samples reduced from 24.5 to 8.0 mg L^{-1} after six hours of sterilization. However, there were no changes in zinc, copper, manganese, iron and lead levels in the water samples after solar exposure.

Effects of mechanical filtration on the physico-chemical properties of water

Filtration of water samples using a PVC mechanical filtration system lead to an improvement of the physico-chemical properties (Table 1). Most physico-chemical properties were reduced to levels below the KEBS maximum permissible limit for potable water (Appendix II).

Table 1 Changes in levels of the physico-chemical properties of water samples before and after mechanical filtration

Physico-chemical property	Before treatment	After mechanical filtration	KEBS standard for potable water
Zn (mg L^{-1})	0.154	0.008	5.0
Cu (mg L^{-1})	0.49	0.072	0.1
Mn (mg L^{-1})	0.51	0.15	0.1
Pb (mg L^{-1})	0.1	0.004	0.05
Fe (mg L^{-1})	1.9	0.6	0.3
Ca (mg L^{-1})	104	34.3	100
NO_3^- N (mg L^{-1})	24.5	4.2	10
SO_4^{-2} (mg L^{-1})	27.7	4.7	400
Cl^- (mg L^{-1})	16.0	2.7	250
pH	7.5	7.1	6.5 - 8.56
Color (mg Pt L^{-1})	119.5	90	15
Turbidity (NTU)	31.5	2.9	5.0
Alkalinity (mg $CaCO_3$ L^{-1})	143	138	500

Effects of mechanical filtration on the presence of selected bacterial isolates in water samples

Results from the present study shows that mechanical filtration was least effective in the removal of *Klebsiella pneumoniae*. Genus *Klebsiella* isolates were detected in eight of the nine replicates (11 % reduction) of distilled water treated with the bacterial isolate before filtration (Table 2). *E. coli*, *S. typhi* and *Clostridium* sp. in the treated water sample were each detected in 5 (44 % reduction), 4 (56 % reduction) and 2 (67 % reduction) replicates respectively while *Vibrio cholerae, Streptococcus* and *Shigella* sp. were all detected in 3 replicates (67 % reduction) after mechanical filtration. Hence, none of the bacterial isolates was completely removed by the mechanical filtration process.

Table 2 Changes in the presence of bacterial isolates in distilled water spiked with a pure culture of the isolate and filtered using the mechanical filter system

Distilled water before mechanical filtration		After mechanical filtration No. of replicates filtered								
Bacteria isolate	**present**	1	2	3	4	5	6	7	8	9
E. coli	+	-	-	+	+	+	-	-	+	+
Klebsiella sp.	+	+	+	-	+	+	+	+	+	+
Salmonella sp.	+	+	+	-	-	-	+	-	+	-
Vibrio cholerae	+	+	+	-	-	-	-	-	+	-
Clostridium sp.	+	-	-	-	+	-	-	-	+	-
Streptococcus	+	-	-	-	+	+	-	-	-	+
Shigella sp.	+	-	-	+	+	-	-	-	-	+

Legend: + Bacterial isolates present; - Bacterial isolate absent

When water samples containing 2.6875×10^4 CFU per 100 mL of total coliforms and 3.9×10^3 CFU per 100 mL of *E. coli* were filtered using the mechanical filtration system, the load of these bacteria reduced to 8.06×10^2 CFU per 100 mL and 1.17×10^2 CFU per 100 mL respectively.

Water treatment using mechanical filtration system made of PVC pipes

Mechanical filtration of water samples using one U shaped and two U shaped pipes (connected in a series) at filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} had different impacts on water quality. An overall increase in total alkalinity from 59 mg $CaCO_3$ L^{-1} to 189, 184, 182, 177 mg $CaCO_3$ L^{-1} and pH from 7.3 to 7.8, 7.7, 7.78, 7.53 was recorded after employing a 1 U-shaped PVC filtration at a filtration rate of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} respectively (Fig. 2). Using the 2U-shaped PVC filtration unit, total alkalinity increased from 59 mg $CaCO_3$ L^{-1} to 145, 163, 175 and 171 while pH rose from 7.3 to 7.74, 7.69, 7.7 and 7.5 respectively (Fig. 3 a & b). Colour reduced from 200 mg Pt L^{-1} to 84, 66, 41 and 26 mg Pt L^{-1} after the samples were filtered through a 1 U PVC pipe at filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} respectively. Using the 2U PVC pipes and the same filtration rates, color reduction to 100, 79, 49 and 31 mg Pt L^{-1} respectively (Figure 3c) was recorded. Sample filtration using the 1 U PVC and 2U pipes at a filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} reduced turbidity from 24 NTU to 13, 1.8, 1.6 and 1.3 NTU (1 U) and to 8.0, 1.2, 1.1 and 0.8 NTU (2 U) respectively (Figure 3 d).

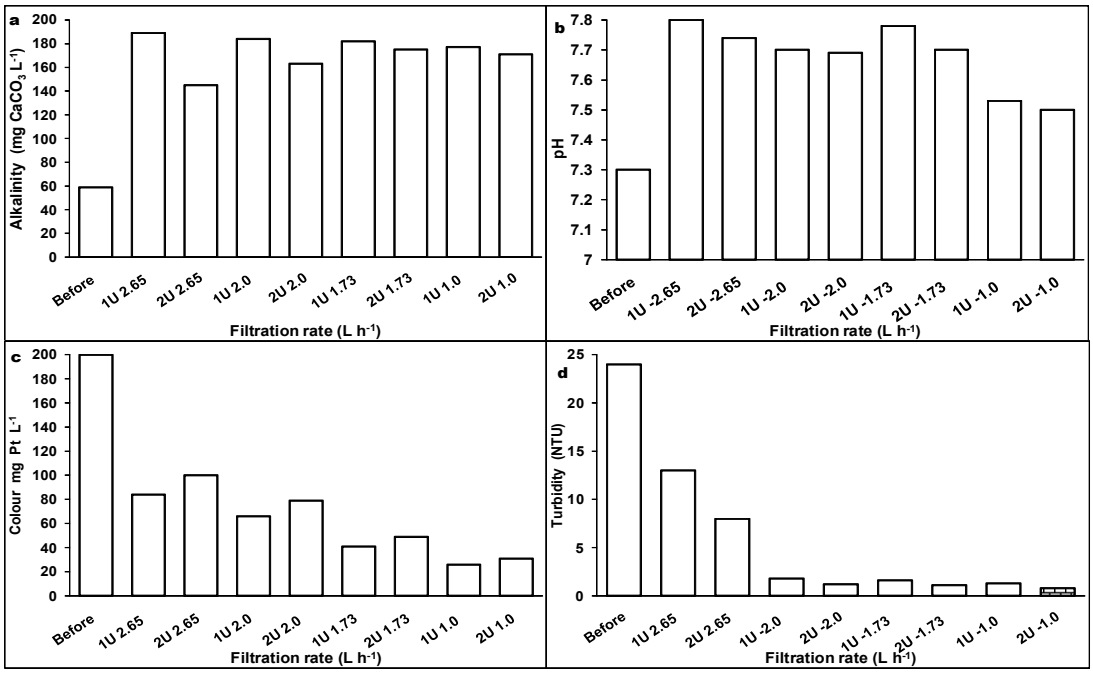

Figure 3 Changes in total alkalinity (a), pH (b), color (c) and turbidity (d) following the mechanical filtration of water samples using one U-pipe and two U-pipes at a filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L $h^{-1}$and 1.0 L h^{-1}

Metal concentration showed a progressive reduction with reducing speed of filtration. Sample filtration at rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} reduced iron concentration from 1.0 mg L^{-1} to 0.48, 0.18, 0.1 and 0.04 mg L^{-1} (using 1 U PVC pipe) and to 0.38, 0.15, 0.08 and 0.02 mg L^{-1} (using 2 U PVC pipe) respectively (Fig. 4 a). Copper reduced from 0.56 mg L^{-1} to 0.15, 0.09, 0.04 and 0.01 mg L^{-1} (using a 1 U PVC pipe) and to 0.13, 0.07, 0.03 and 0.0 mg L^{-1} (using a 2 U PVC pipe) at a filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} respectively (figure 4 a). Zinc concentration in water samples reduced from 0.28 mg L^{-1} to 0.21, 0.14 and 0.0 mg L^{-1} when a 1 U PVC pipe was used filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} while using a 2 U PVC pipes at the above filtration rates reduced to 0.19, 0.11 0.0 and 0.0 mg L^{-1} respectively (figure 4b). For the same filtration rates, manganese reduced from 0.24 mg L^{-1} to 0.09, 0.05, 0.02 and 0.0 mg L^{-1} and to 0.08, 0.03, 0.01 and 0.0 using a 1U and 2 U PVC pipes respectively (Fig.4b). Lead concentration in water samples reduced from 0.1 mg L^{-1} to below detection limit after filtration using a 1 U and 2 U PVC pipes (Fig.4b). Nitrate nitrogen in water samples reduced from 32 mg L^{-1} to 15, 12, 10 and 7.0 mg L^{-1} (1 U PVC pipe) and to 18, 14, 12 and 8.5 (2 U PVC pipe) at filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L $h^{-1}$and 1.0 L h^{-1} (figure 4c).

Passage of water samples contaminated with 6×10^3 CFU per 100 mL of total coliforms and 4.82×10^3 CFU per 100 mL of *E. coli* using 1 U PVC pipe at filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} reduced the total coliforms to 9.6×10^1, 6.7×10^1, 4.0×10^1 and 2.0×10^1 CFU per 100 mL while the *E. coli* reduced to 7.6×10^1, 5.6×10^1, 3.2×10^1 and 1.5×10^1 CFU per 100 mL respectively (Figure. 4.d). Filtration of the water samples using 2U PVC pipes at filtration rate of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L h^{-1} and 1.0 L h^{-1} reduced the total coliforms from 6.0×10^3 CFU per 100 mL to 6.9×10^1, 4.5×10^1, 2.7×10^1 and 1.3×10^1 CFU per 100 mL while the *E. coli* reduced from 4.82×10^3 CFU per 100 mL to 5.3×10^1, 3.7×10^1, 2.1×10^1 and 9.0×10^{-1} CFU per 100 mL respectively (figure. 4.d).

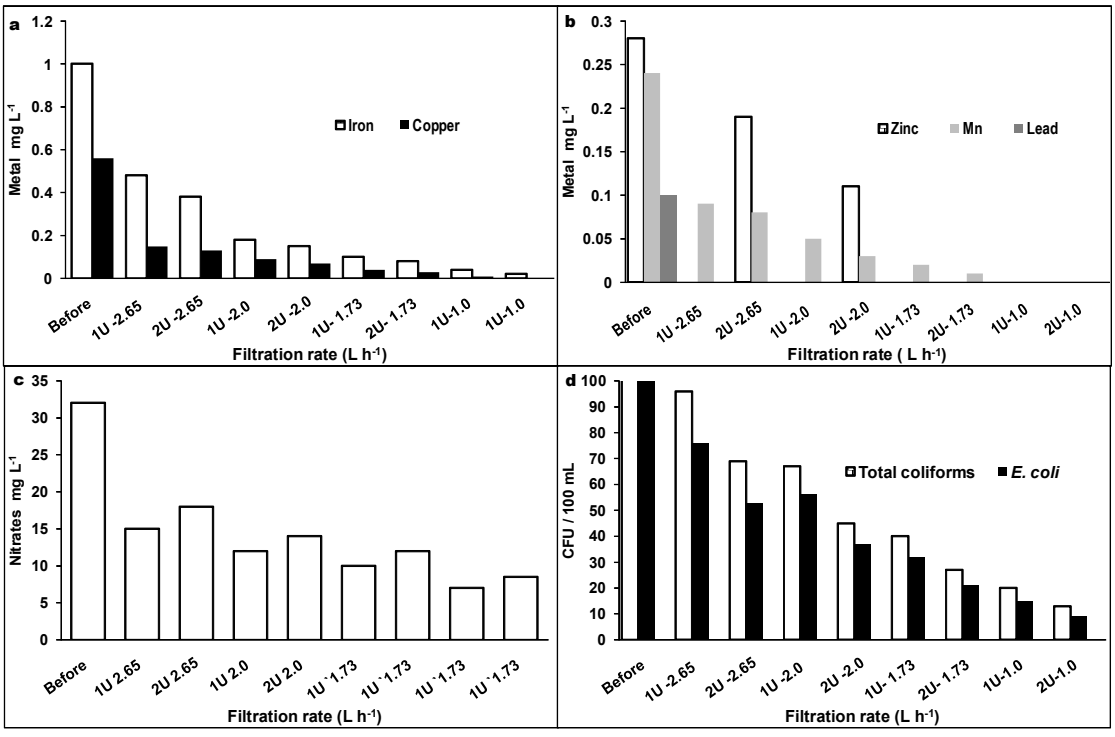

Figure 4 Changes in the concentration of selected metals (a & b), nitrate nitrogen (c), and bacterial reduction (d) following the mechanical filtration of water samples using a 1 U and 2 U PVC pipes at a filtration rates of 2.65 L h^{-1}, 2.0 L h^{-1}, 1.73 L $h^{-1}$and 1.0 L h^{-1}

DISCUSSION

Water treatment by Mechanical filtration

Although the sand filter removed about 97% of *E. coli* and total coliforms, the water produced did not meet potable water standards of 0.0 CFU per 100 ml for total and faecal coliforms according to the water quality standards set by KEBS and WHO. Filtration reduced the number of the bacteria but not to potable level. Sand filtration only made the water easier for treatment using other treatment options. One of the requirements for the slow sand filter is that the sand needs to be very fine (0.1 to 0.35 mm diameter). Although no grain size measurements were made during the present study, it is possible that the sand used did not meet the grain size requirements. Similarly, the raw water to be filtered should be treated to about 20 NTU or less unlike the 31 NTU that was used in the present study. The high turbidity of the raw water blocks the sand filter faster, shortening the time between cleanings and lowering the water quality. The removal of sediments and trace metals was greater than the removal of soluble pollutants like nitrates (from 24.5 mg L^{-1} to 4.16 mg L^{-1}), chlorides (from 14 mg L^{-1} to 2.38 mg L^{-1}) and sulphates (from 29.1 mg L^{-1} to 4.95 mg L^{-1}) since the mechanical filter functions primarily by mechanical straining. High amounts of trace metals were easily removed possibly because of adsorption to particulate matter (Cu from 1.1 mg L^{-1} to 0.06 mg L^{-1}, Zn from 0.16 mg L^{-1} to 0.08 mg L^{-1}, Pb from 0.08 mg L^{-1} to 0.003 mg L^{-1}). Sand filtration mimics the natural purification of spring water.

Mechanical filtration of water samples using a single (1 U) and double (2 U, arranged in series) at filtration rates of 2.65, 2.0, 1.73 and 1.0 L h^{-1} resulted in an increase in the total alkalinity of the water samples. An increase in alkalinity from 59 mg $CaCO_3$ L^{-1} to a maximum of 189 mg $CaCO_3$ L^{-1} may not pose a significant threat to use of the water for domestic purposes (**Pande and Sharma, 1999**). Although, both the 1 U and 2 U PVC pipes filtration systems removed a significant amount of contamination (e.g. reduction in the concentration of metals, nitrates colour, total coliforms etc.), presence of total coliforms were still detected in the filtered water. Hence, the filtration system did not produce water that meets the WHO (2006) and KEBS (1996) standards for drinking water. However, a significant reduction in total coliforms and *E. coli* confirms the potential of the filtration as a tool for household-scale water treatment. The overall reduction in contaminant load by the PVC pipe system filtration can be associated with the adsorption of contaminants on the filter medium and physical straining, which is the main mechanism by which filter beds remove particulate matter (**Weber-Shirk *et al.*, 1997**). Use of PVC pipes increased the surface area of contact thereby increasing the physical straining and hence higher quality efficient in filtration (**Bellamy *et al.*, 1985**). The results also revealed that the lower the filtration rate, the more the effective the system becomes in contaminant removal. Comparing the four-filtration rates, a filtration rate of 1.0 L h^{-1} was the best for the eradication of total coliforms, *E. coli* and other pathogenic microorganisms to potable standards according to KEBS and WHO. However, the clean water yield was too little. Filtration using 2 U PVC pipe system provided better quality water than the 1 U PVC pipe system in terms of improving the physico-chemical and bacteriological quality. This can be accounted for by the higher surface area of contact resulting from the greater length of the 2 U pipe systems. Overall, the PVC pipe filtration system was more effective in reducing the load of total coliforms (reduced from 6.0×10^3 to 8.06×10^2 CFU/100 mL and from 6.0×10^3 to about 2.0×10^1 CFU/ 100 mL for the system using plastic container system and PVC pipe system respectively) and *E. coli* (reduced from 4.82×10^3 to 1.17×10^2 CFU/ 100 mL and from 4.82×10^3 to about 1.5×10^1 CFU/ 100 mL for large plastic container system and PVC pipe system respectively) as compared to the above-ground large plastic filtration system constructed using 100 L capacity plastic containers (figure 1).

Solar irradiation

Solar irradiation is a low-cost alternative for water disinfection by use of solar energy, which can be employed by rural communities. A higher disinfection rate (eradication of *E. coli* after 45 minutes, Streptococci after 75 minutes, *Shigella* & *Klebsiella* after 90 minutes and all of the pathogenic microorganisms after 4 hours) achieved when transparent bottles were placed on house roof tops (iron sheets) as compared to when transparent bottles were placed on the ground on black polythene paper surface (eradication of total coliforms after 75 minutes, Streptococci after 90 minutes, *Shigella* and *Klebsiella* after 2 hours and all of the pathogenic microorganisms after 6 hours) can be attributed to high temperatures and UV light intensity attained when the transparent bottles were placed on iron sheets.

The difference in the rate of disinfection of water by transparent polythene papers commonly used for packaging edibles (total coliforms reduced from 2.6875×10^4 CFU per 100 ml to 11, 3, 1 and 0 CFU per 100 ml after 1 hour, 2 hours, 4 hours and 6 hours exposure respectively while the *E. coli* reduced from 3.9×10^3 CFU per 100 ml to 8, 4, 2 and 0 CFU per 100 ml after 1 hour, 2 hours, 4 hours and 6 hours exposure respectively) compared to using transparent dasani/mineral water containers (total coliforms reduced from 2.6875×10^4 CFU per 100 ml to 13, 7, 2 and 0 CFU per 100 ml after 1 hour, 2 hours, 4 hours and 6 hours exposure respectively while the *E. coli* reduced from 3.9×10^3 CFU per 100 ml to 10, 5, 3 and 0 CFU per 100 ml after 1 hour, 2 hours, 4 hours and 6 hours exposure respectively) can be attributed to a difference in UV light penetration with greater penetration in transparent polythene papers as compared to the transparent dasani/ mineral water plastic bottles. Use of solar radiation to inactivate bacteria and other pathogens can therefore be the simplest and least expensive methods of providing safe drinking water to rural communities.

A number of factors such as predation, desiccation and lack of nutrients, sub-optimal pH, temperatures and metal toxicity influence the survival of bacteria in water. Since a variety of heavy metals are found at elevated concentrations in contaminated water, the effect of metal toxicity may play a significant role in regulating bacterial populations hence besides solar disinfection, the reduction of bacteria could be associated with metal toxicity.

A reduction in total coliforms and *E. coli* to 0 CFU per 100 mL after 6 hours of solar exposure confirms that solar exposure for a period of 6 hours is effective in removing all bacteria in water samples. Removal of total and faecal coliform bacteria was significantly higher when polyethylene bags were exposed to sunlight compared to samples left in rooms with artificial light or completely in the dark (**Acra *et al.*, 1990**). The bactericidal effect of sunlight or photo disinfection is due to the combined action of ultraviolet (UV) radiation and several wavelengths of the spectrum. Both the ionizing radiation of UV rays and electromagnetic radiation of visible light can damage cells, killing them in the process. The effect is based on damaging key molecules such as nucleic acids, either separating them physically in such a way that they reproduce incorrectly or by photochemical reactions that lead to errors in the subsequent synthesis of proteins, in such a way that the organism is unable to survive (**Hooper, 1987**).

In general, the effectiveness of solar disinfection is determined by factors such as intensity of sunlight and exposure time, type of bacteria, nature and composition of the medium and the presence of nutrients capable of maintaining growth and reproduction of the microorganisms, type and characteristics of containers, degree of turbidity, and the volume and depth of the water (**Carlson, 2003; Conroy *et al.*, 1999; WHO, 1996 c**). The results obtained after solar disinfection therefore shows that total coliform removal is more effective in polyethylene bags of three to six liters where a 99% removal was achieved after four hours of exposure.

CONCLUSION

Mechanical filtration and solar disinfection of water did not make the water potable in terms of bacteriological and physico-chemical quality respectively as per the KEBS and WHO water drinking standards. When each of the two methods of treatment was used independently, it did not treat the water to potable status. Mechanical filtration improved physico-chemical properties such as color, turbidity, nitrate nitrogen, chlorides and some metals.

Solar disinfection was found to be effective in eliminating the bacteria after 6 - 8 hours exposure but did not have any appreciable impact on the physico-chemical properties of the water.

RECOMMENDATIONS

A combination of both mechanical filtration and solar disinfection can be employed in making the water potable. Genotoxic effect of plastic bottles used in solar disinfection should be conducted to determine whether there is any potential danger to those consuming the treated water.

Acknowledgments: The authors would like to thank Plant and Microbial Sciences department, Kenyatta University for provision of laboratory reagents and equipment and Thika water and Sewerage Company Ltd for physico-chemical analysis of water samples.

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APPENDICES

Appendix I Recommended drinking water standards by WHO (WHO, 2006 b)

Property of water	Highest desirable levels	Maximum permissible level
Turbidity	5 NTU	10 NTU
Color (units on platinum)	5	25
Chlorine (residual level)	0.20 mg L^{-1}	1.0 mg L^{-1}
pH	7.0-8.0	9.2
Salinity	500 mg L^{-1}	1000 mg L^{-1}
Chlorides	200 mg L^{-1}	600 mg L^{-1}
Sulphates	200 mg L^{-1}	400 mg L^{-1}
Nitrates	45 mg L^{-1}	45 mg L^{-1}
Fluorides	1.0 mg L^{-1}	1.0 mg L^{-1}
Iron	0.1 mg L^{-1}	1.0 mg L^{-1}
Manganese	0.05 mg L^{-1}	0.5 mg L^{-1}
Calcium	75 mg L^{-1}	200 mg L^{-1}
Magnesium	30 mg L^{-1}	150 mg L^{-1}
Zinc	5.0 mg L^{-1}	15 mg L^{-1}
Copper	0.05 mg L^{-1}	1.5 mg L^{-1}
Total hardness	100 mg L^{-1}	500 mg L^{-1}
Phenol	0.001 mg L^{-1}	0.002 mg L^{-1}
Arsenic	0.05 mg L^{-1}	0.05 mg L^{-1}
Cyanide	0.05 mg L^{-1}	0.05 mg L^{-1}
Lead	0.1 mg L^{-1}	0.1 mg L^{-1}
Selenium	0.01 mg L^{-1}	0.01 mg L^{-1}
Mercury	0.001 mg L^{-1}	0.001 mg L^{-1}
Taste and odor	Unobjectionable	Unobjectionable

Appendix II Recommended drinking water standards according to the Kenya Bureau of Standards (Source: Adopted from KS 05-459: Part 1:1996)

PARAMETER	UNIT	KS 05-459 REQUIREMENT
pH	pH Scale	6.5-8.56
Color	mg pt L^{-1}	15
Turbidity	NTU	5 Max
Permanganate value (20 min boil)	mgO_2 L^{-1}	10 Max
Conductivity	µS cm^{-1}	2500
Iron	mg L^{-1}	0.3 Max
Manganese	mg L^{-1}	0.1 Max
Calcium	mg L^{-1}	100 Max
Magnesium	mg L^{-1}	100
Sodium	mg L^{-1}	200
Potassium	mg L^{-1}	50
Total hardness	mg $CaCO_3$ L^{-1}	500
Total alkalinity	mg $CaCO_3$ L^{-1}	500
Chloride	mg L^{-1}	250 Max
Fluoride	mg L^{-1}	1.5 Max
Nitrate nitrogen	mg L^{-1}	10 Max
Nitrites	mg N/l	0.1 Max
Sulphate	mg L^{-1}	400
Total suspended solids	mg L^{-1}	Nil
Free carbon dioxide	mg L^{-1}	
Total dissolved solids	mg L^{-1}	1500 Max
Copper	mg L^{-1}	0.1
Zinc	mg L^{-1}	5
Ammonia nitrogen	mg L^{-1}	0.5
Fluorides*	mg L^{-1}	1.5
Arsenic	mg L^{-1}	0.05
Cadmium	mg L^{-1}	0.005
Lead	mg L^{-1}	0.05
Mercury	mg L^{-1}	0.001
Selenium	mg L^{-1}	0.01
Chromium	mg L^{-1}	0.05
Cyanide	mg L^{-1}	0.01
Phenolic substances	mg L^{-1}	0.002
Barium	mg L^{-1}	1.0
Nitrates	mg L^{-1}	10
Type of micro-organism	**Per 100 ml**	
Total viable counts at 37 ^{o}C per ml	100	
Coliforms in 250 mL	CFU	Shall be absent
E. coli in 250ml	CFU	Shall be absent
Staphylococcus aureus in 250ml		Shall be absent
Sulphite reducing anaerobes in 50ml		Shall be absent
Pseudomonas aeruginosa fluorescence in 250ml		Shall be absent
Streptococcus faecalis		Shall be absent
Shigella in 250ml		Shall be absent
Salmonella in 250ml		Shall be absent