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Impacts of storage tanks under the indirect cold water supply system on household water quality: a case of Wakiso District, Uganda

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ABSTRACT

Water supply systems form one of the most fundamental components of building services. In many communities, especially in developing countries like Uganda, most households use the indirect cold water supply system, particularly because of the intermittent water supply problems. However, research has linked the main component of this system, particularly water storage tanks, to the contamination of water. There is a paucity of research regarding which features of these tanks contribute to water contamination. This study investigated the effects of storage tank features and cleaning practices on water quality. The results revealed that the treated water received by households became significantly ($\alpha = 0.05$) contaminated with faecal coliforms ($p = 0.001$), total coliforms ($p < 0.001$), and heterotrophic bacteria ($p < 0.001$) while in storage tanks. Furthermore, Fe and Mn significantly increased in stored water (with $p = 0.001$, and $p = 0.023$, respectively) while residual free chlorine significantly reduced ($p < 0.001$). The study revealed that tank type, tank connectors, and tank age significantly affect water quality. The study concluded that tank cleaning does not guarantee improvement in the quality of stored water. Further research is recommended to determine the best tank cleaning methods and optimal cleaning frequency.

Key words: indirect cold water supply system, tank cleaning, tank features, water quality

HIGHLIGHTS

- Water storage tanks caused significant contamination of stored water.
- 60% of households did not clean their water storage tanks.
- Improper tank cleaning methods and tools led to contamination of stored water.
- Tank cleaning does not guarantee improvement in water quality.
- Stored water quality was most affected by tank material.

INTRODUCTION

Water quality is one of the main challenges that societies will face during the 21st century, threatening among other things human health and hindering economic growth (Nienie *et al.* 2017; UNESCO 2020). Increasing wastewater loading to water bodies has been identified as a leading cause of this great challenge (UNEP 2016). It is through this that many pathogens are introduced into the water supply network. This challenge is more intense in developing countries including Uganda where up to 8 million people still lack access to safe drinking water (Water.org. 2020). This is further aggravated by the intermittent water supply problem that is still a challenge to hundreds of millions of people around the world, especially in low- and middle-income countries (Kumpel & Nelson 2016). This forces many households to store water for daily use in homes (Majuru *et al.* 2016). For this reason, many households choose to use the indirect cold water supply system.

The indirect water supply system is preferred to the direct cold water supply system because it incorporates storage in the form of overhead tanks where water from the mains is first stored before running to sanitary fittings in the house, except the kitchen

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sink (Manga *et al.* 2021). This is because the issue of intermittent water supply can be minimised. However, while the risk of water contamination is significantly lower under direct cold water supply systems, the reverse is true for indirect water supply systems. This is especially because of the storage aspect which is a high-risk contamination component of indirect cold water supply systems, as revealed by different studies such as Schafer & Mihelcic (2012). Water storage often using tanks/vessels is envisaged to be a source of water contamination, along with related user practices (Manga *et al.* 2021). This makes the quality of water under the indirect cold water supply a concern, given that water storage is the main component of this system.

In Uganda, the responsibility to supply and manage the quality of municipal water lies with the National Water and Sewerage Cooperation (NWSC). However, NWSC's responsibility for the quality of the water they supply ends at the metering point, i.e., before the water reaches the storage tank or any appliance. Beyond this point, the management of the quality of water under the indirect cold supply system is the responsibility of the household owners or occupants. Unfortunately, however, there are no known written guidelines in Uganda to help household owners under indirect cold water supply systems in managing household water quality beyond the metering point. For this reason, many people do not pay attention to the quality of water in their households. This has resulted in poorly managed water storage tanks with poor water quality that has increased the prevalence of waterborne diseases, in peri-urban and urban areas in Uganda that can be directly linked to the consumption of contaminated water (Ssemugabo *et al.* 2019). This study, therefore, focused on investigating the impacts of the water storage components of the indirect water supply systems and the associated household practices on stored water quality. The aim of the study was to determine the effects of the tank features and tank cleaning on household water quality and to develop a model for predicting water quality in the indirect cold water supply system.

MATERIALS AND METHODS

Study design and sample collection

Selection of water storage tanks for the study

A systematic literature review that was recently published was carried out to identify storage tank features that may have an effect on household water quality (Manga *et al.* 2021). Features that were investigated most, i.e. tank material/type, tank age, tank size/retention time, and tank cleaning were considered for the study. A pre-study was then carried out from November 2019 to January 2020 to identify and select tanks for the study. This was done by conducting community transect walks and field observational survey during which in total 512 households were identified. In total, 354 households that had the indirect cold water supply system gave positive consent for the study, tanks that were accessible and tanks with features that would best answer the research objectives were purposively selected, forming the sampling frame. In total, 112 household water storage tanks were then randomly selected from the sampling frame for the study.

Data collection

Household surveys and structured observations. Prior to sample collection at each selected household, the storage tank user's survey and structural observations were conducted to collect information on the characteristics of the tanks and household. These surveys/interviews targeted household heads or any members knowledgeable about household water usage and practices. The user's surveys collected information on (a) the number of household members, (b) capacity/volume of the water storage tanks (c) age of the water storage tank, (d) tank cleaning frequency, (e) when the water tank was last cleaned, (f) method used for tank cleaning, (g) cleaning tools and materials, and (h) challenges faced when cleaning the tanks. The structural observations were used to collect data on (a) material type of the water storage tank, (b) location of the washout pipe, (c) condition of the tank material especially the steel tanks and galvanised iron (GI) connectors (e.g., whether corroded or not), (d) presence of bio-film or settled solids at the tank bottle or sides, and (e) physical appearance of the water in the tank. The data collected through these household surveys were used in the assessment of the user practices, material types, and conditions of the water storage tanks. Prior to data collection, all the surveys were independently checked, pretested and piloted in non-study villages.

Sample collection. In total, 112 household water storage tanks were selected and sampled during June through August 2020. During each sampling phase, two sets of samples were collected from a selected household water storage tank: (i) the first one from the water inflowing to the storage tanks, using grab sampling technique, to ascertain the quality of water that was flowing into the water storage tanks; and (ii) the second one from the water flowing out of the storage tank to the household sanitary appliances, in order to determine the quality of water leaving the storage tank. Sampling was done monthly in three phases from the same tanks.

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Samples for physicochemical analysis were collected in clean 1-litre plastic bottles rinsed on-site with the sample water prior to filling the sample bottles, while those for microbial analysis were collected in 250-ml plastic and glass bottles pre-sterilised in an autoclave and containing sodium thiosulphate to neutralise residual chlorine. Samples bottles (glass) for heavy metals were rinsed with, and soaked in, nitric acid solution to prevent precipitation of heavy metals in the water samples. Samples were kept in iced cool boxes during collection (to stops enzyme activity, therefore stopping the bacteria from growing), and transported to Bugolobi NWSC Central Laboratory for analysis.

Flow measurements. At each sampling site, the household water meter readings were taken at 24-hour intervals for 3 days in order to determine the household water usage and flow rate. However, as majority of the selected households (about 97%) had indirect water supply system designed and constructed with all the water flowing to the sanitary appliances going through the water storage tanks, the 3-day water meter readings were used to compute the average daily water usage and flow rate to and from the storage tank. Then, based on the daily water flow rate and volume of the storage tanks, the water storage periods or hydraulic retention time of water in the tanks were computed.

Sample analysis

Temperature and free chlorine were tested in the field using a water thermometer and Palintest Chlorometer Duo, respectively. For the rest of the water quality parameters, samples were kept refrigerated in the laboratory and analysed in less than 24 hours. *E. coli*, faecal coliforms, total coliforms, and heterotrophic bacteria were analysed within 12 hours of sample collection. A holding time of up to 30 hours was initiated for drinking water samples to be analysed for the above-mentioned bacteriological parameters (EPA 2016). To confirm the specific presence of faecal contamination, only samples that had tested positive for faecal coliforms were further tested for *E. coli*. This is because *E. coli* provides conclusive evidence of recent faecal contamination and should not be present in drinking water (WHO, Guidelines for drinking-water quality 2017). In addition, not all coliforms that possess thermotolerant properties may be of faecal origin (Bartram & Ballance 1996). A membrane filtration technique was used for the analyses, following the standard methods for the examination of water and wastewater (APHA 2017). This a high precision technique as results are obtained directly by colony count, compared with the alternative technique of multiple fermentation tube in which results are obtained indirectly by statistical approximation (Bartram & Ballance 1996). The other physicochemical parameters (turbidity, pH, conductivity, total dissolved solids, dissolved oxygen, NO_3^-, SO_4^{2-}, PO_4^{3-}, Mn, Pb, Zn, and Fe) were also analysed following standard methods for the examination of water and wastewater (APHA 2017).

Data analysis

Results from sample analyses, tank user's structured interviews, and observational surveys were organised, tabulated in a Microsoft Excel 2019 file (Supplementary Information) and exported to IBM SPSS version 25 for statistical analyses. Firstly, a comparison of inflowing water to the tanks and outflowing water from the storage tank water was done to determine whether the deterioration in water quality while in tanks was significant. This was done using one-way analysis of variance (ANOVA) and Kruskal–Wallis ANOVA depending on the normality of the data set, and statistical significance, which was determined at a 95% confidence interval. Parameters that significantly varied between the water flowing in and out of the tank were carried forward for further analysis to determine how the features of the storage tanks affected them. To assess how water quality was affected by the various tank features and cleaning, groups of the tank features were created and water quality indicators compared between the groups using the above-mentioned statistical methods. All significant tests were followed by pairwise post-hoc Kruskal–Wallis tests to check the difference in means between each group of the tank features. Furthermore, a multivariate binary logistic regression model was developed to predict water quality in storage tanks under the indirect cold water supply system. Prior to the modelling, the dataset was first recoded to 1 and 0 to represent unacceptable and acceptable quality of water respectively, based on Ugandan Standards for treated drinking water. For purposes of better presentation of the data, the data were then exported back to a Microsoft Excel 2019 file and the tables and figures generated accordingly.

RESULTS AND DISCUSSION

Quality of tank inflow water vs tank outflow water

We undertook to compare the quality of water flowing into the tanks and that flowing out of the tanks. Table 1 presents the results of the microbiological analysis of the water samples before (tank inflow) and after storage (tank outflow). It can be noted from Table 1 that storage tanks significantly affected the microbial quality of water.

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Table 1 | Microbiological parameters of water flowing to and from the water storage tank

Parameter	**Mean** **Tank inflow**	 **Tank outflow**	**SIG. ($\alpha = 0.05$)**
E. coli (CFU/100 ml)	0	0	N/A
Faecal coliforms (CFU/100 ml)	0	1	0.001*
Total coliforms (CFU/100 ml)	0	19 ± 2	<0.001*
Heterotrophic bacteria (CFU/100 ml)	0	772 ± 104	<0.001*

*Significant difference; N/A = Not applicable.

All the four indicators of microbial quality of water that were tested, *E. coli*, faecal coliforms, total coliforms, and heterotrophic bacteria, were absent in the water flowing into the tanks. In contrast, faecal coliforms, total coliforms, and heterotrophic bacteria were present in significantly high concentrations in the water from the storage tanks ($p < 0.001$), with mean values of 1 CFU/100 ml, 19 CFU/100 ml, and 772 CFU/100 ml, respectively. Interestingly, *E. coli* was absent in the water outflowing from the storage tank. The findings of this study are consistent with those of previous studies such as Al-Bahry *et al.* (2013), who also found no heterotrophic bacteria and total coliforms in the water received by households but high concentrations in residential storage tanks.

Our results suggested that storage tanks provide favourable conditions for bacteria regrowth. However, as reported by previous studies such as Bartram & Ballance (1996), the presence of bacteria in tanks may not necessarily mean there is a significant health risk to household members. However, the presence of *E. coli* in drinking-water samples almost always indicates recent faecal contamination (Reddy 2011), meaning that there is an increased risk that pathogens may be present. Therefore, the absolute absence of *E. coli* from the water sampled from the storage tanks in this study suggested that household members did not have high risks of contracting waterborne diseases, despite the fact that there was substantial regrowth of other bacteria in the tanks.

Table 2 presents the variations in the physicochemical parameters of water flowing to and from the water storage tanks. Our results revealed that storage tanks have an effect on the physicochemical quality parameters of water. The significant

Table 2 | Physicochemical parameters of water flowing to and from the storage tanks

Parameter	**Mean** **Tank inflow**	 **Tank outflow**	**SIG. ($\alpha = 0.05$)**
Free chlorine (mg/L)	0.24 ± 0.02	0.05 ± 0.01	*<0.001
Turbidity (NTU)	0.75 ± 0.06	0.87 ± 0.06	0.178
Temperature (°C)	24.00 ± 0.14	24.15 ± 0.24	0.647
DO (mg/L)	7.60 ± 0.05	7.47 ± 0.07	0.142
Colour (Pt Co)	6.97 ± 0.71	10.68 ± 1.11	*0.008
EC (µS/cm)	99.08 ± 0.78	102.76 ± 2.34	0.299
TDS (mg/L)	63.44 ± 0.50	65.77 ± 1.50	0.332
pH	7.47 ± 0.04	7.49 ± 0.04	0.484
SO_4^{2-} (mg/L)	7.20 ± 0.20	6.07 ± 0.19	*<0.001
PO_4^{3-} (mg/L)	0.04 + 0.01	0.05 ± 0.01	0.351
NO_3^- (mg/L)	0.00	0.01 ± 0.01	0.665
Mn (mg/L)	0.008 + 0.01	0.013 + 0.001	*0.023
Fe (mg/L)	0.04 ± 0.01	0.09 ± 0.02	*0.001
Pb (mg/L)	<**0.07**	<**0.07**	N/A
Zn (mg/L)	<**0.04**	<**0.04**	N/A

*Significant difference; N/A = Not applicable.

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reduction of free chlorine in the stored water means that the storage water tanks cause decay of chlorine. As reported by previous studies such as Kowalska *et al.* (2006), chlorine is a chemical compound that reacts with the various other organic and inorganic compounds in the tanks to form other products, hence reducing its concentration in the tanks. Although the concentration in the water received by households (mean value = 0.24 mg/L) met the standard of 0.2 to 0.5 mg/L, the significant reduction in storage tanks to 0.05 mg/L ($p < 0.001$) implied that the level of disinfection of the supplied water was adequate only for water that is immediately used, such as under the direct cold water supply system. Under the indirect cold water supply system, where water may be stored in tanks for days, a higher concentration of residual free chlorine is needed in order to reduce bacterial regrowth.

The significant increase in colour and heavy metals manganese (Mn) and iron (Fe) after storage can be attributed majorly to corrosion of galvanised steel tanks and GI connectors, and sediments from the supplied water. Sulphate concentrations remained within standard levels both before and after water flows from the storage tanks. Turbidity, temperature, DO, pH, EC, TDS, PO_4^{3-}, NO_3^-, Pb, and Zn were not significantly affected by tanks, therefore were not carried forward for further analyses.

Effect of storage tank types/materials on water quality

Figure 1 presents the results of bacteriological analysis of the water from three tank materials studied. The materials used for water storage tanks in study area included stainless steel, plastic (black in colour), and galvanised steel.

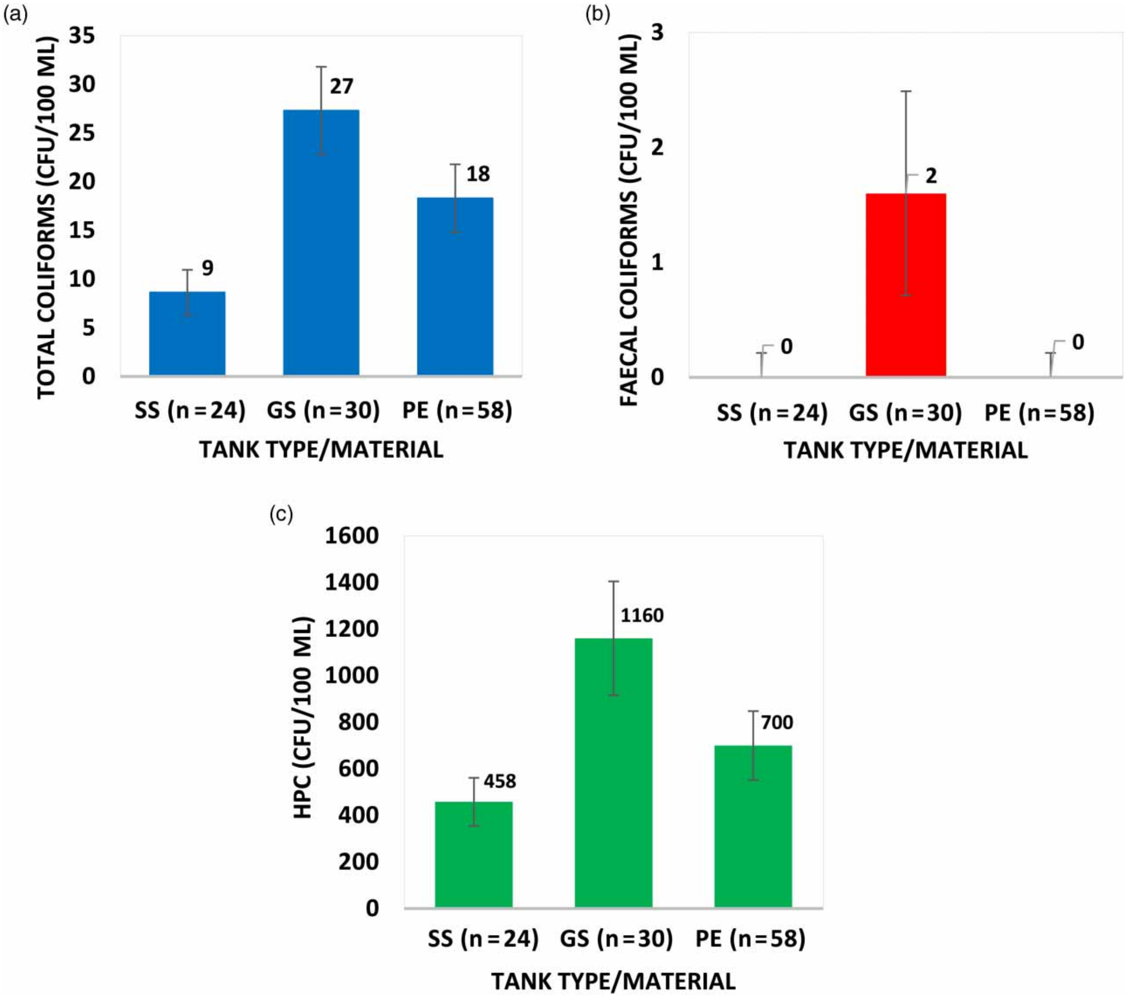

Figure 1 | Concentrations of bacteria in water flowing from three water storage tank types; (a) total coliforms; (b) faecal coliforms; (c) heterotrophic bacteria. Error bars represent the standard error around the mean values. SS = stainless steel tanks; PE, plastic tanks; GS, galvanised steel tanks. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2021.411.

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It can be noted from Figure 1 that water outflowing from the galvanised steel tanks recorded the highest concentration of faecal coliforms, total coliforms, and heterotrophic plate count (HPC) with mean values of 2 CFU/100 ml, 27 CFU/100 ml, and 1,160 CFU/100 ml. However, that flowing from the stainless steel tanks conversely had the lowest concentrations of faecal coliforms, total coliforms, and HPC (0 CFU/100 ml, 9 CFU/100 ml, and 458 CFU/100 ml, respectively).

These study results revealed that there are statistically significant differences in total coliform levels ($p = 0.010$) and HPC ($p = 0.018$) in water from the three tank material/types. Our results are in agreement with previous similar studies that also reported variations in water quality as a result of storage tank material (Schafer & Mihelcic 2012; Akuffo *et al.* 2013)**.** However, our results contradict those of Evison & Sunna (2001) who found no influence of tank material on total bacteria counts. The possible explanation for this contradiction could be the types of tanks that were considered in the studies, because water quality may not significantly vary between all tank types. Further, the pairwise post-hoc Kruskal–Wallis test revealed that total coliforms varied significantly only between stainless steel and galvanised steel tanks ($p = 0.012$), and not between plastic and galvanised steel tanks, and plastic and stainless steel tanks. HPC did not significantly vary between plastic and stainless steel tanks but varied significantly between plastic and galvanised steel tanks ($p = 0.032$), and stainless steel and galvanised steel tanks ($p = 0.046$). The varying concentrations of bacteria in the three tank types were likely because of the differing physical conditions of the tanks (see Figure 2), and the nature of the materials themselves.

Galvanised steel tanks were generally in poor condition, with corroded interior surfaces. Zinc coating on galvanised steel tanks is meant to provide corrosion protection, however Smith & Goodwin (2017) reported that it may itself be a source of corrosion. Bimetallic corrosion is expected to occur when the steel surfaces of the galvanised steel tanks are exposed, among other things, by cut surfaces and drilled holes, such as those used to secure inlet and outlet pipes, washouts, and ball valves. This likely explains the observation of deeper corrosion around pipe fittings on the galvanised steel tanks, particularly around ball valve fittings.

Corrosion deposits were observed in at least 50% of plastic tanks, resulting from the use of GI tank connectors. However, they were not as many deposits as that observed in galvanised steel tanks. Conversely, stainless steel tanks were not corroded,

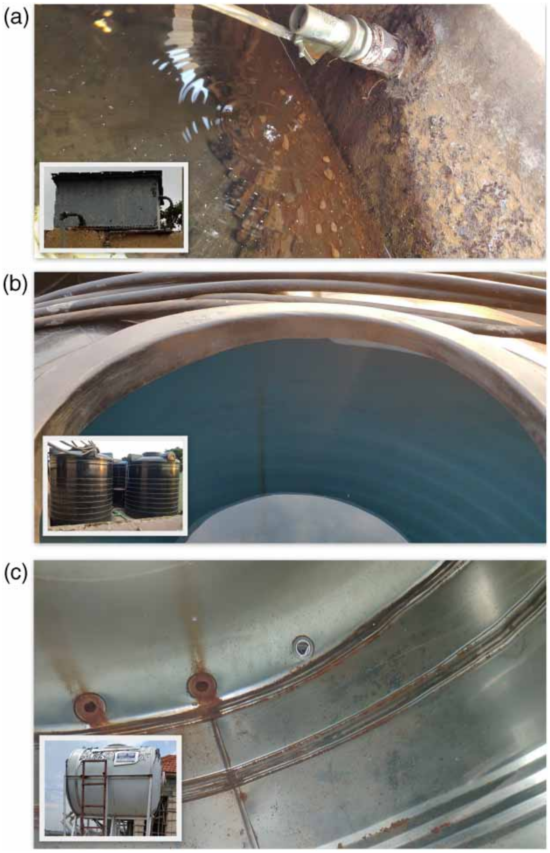

Figure 2 | Material types of the water storage tanks observed in the study area, (a) galvanised steel tank, (b) plastic tank, and (c) stainless steel tank. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2021.411.

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except for the small amounts of corrosion around the GI tank connectors. This is a special advantage stainless steel tanks have of corrosion resistance. Corrosion products have been found to be a source of nutrients for some bacteria, and to encourage micro-aquatic bacterial growth and a build-up of biofilm (Lemon 2020). The vast amount of corrosion observed in galvanised steel and plastic tanks may have therefore provided many nutrients for the regrowth of bacteria in the tanks. This could be why, as shown in Figure 1, water from galvanised steel tanks recorded more bacteria concentrations, followed by plastic tanks, while stainless steel recorded the lowest.

Furthermore, most plastic tanks had surfaces covered with biofilm. Previous research has strongly associated plastic tanks with biofilm. For example, Rogers *et al.* (1994) reported that crevices and hollows in plastic tank surfaces resulting from their manufacture allow for rapid colonisation by bacteria and dense biofilm to form. Biofilm provides a conducive environment for microbial regrowth (Al-Bahry *et al.* 2013). By contrast, stainless steel tanks were observed to have less biofilm. A study done in 1994 had a similar finding of least biofilm formation and pathogen growth on stainless steel tanks compared with plastic and mild steel tanks (Rogers *et al.* 1994). This is most likely why stainless steel tanks in the present study demonstrated evidence of the least bacterial growth. In the same vein, rough surfaces are generally found to have more adhesion, therefore it is possible that the crevices on plastic tank surfaces and the corroded rough surfaces of the galvanised steel tanks allowed particulates in the water that may have included nutrients for bacteria to stick to tank surfaces. Stainless steel tank surfaces conversely had very smooth surfaces that discouraged substances from sticking to the tank surfaces, thereby keeping them much cleaner than the other two types of tanks.

Table 3 presents the results from the physicochemical analysis of water samples from the different tank materials. It can be observed from Table 3 that there is a significant difference in the colour ($p = 0.018$) of the water from the different tank materials. The significant difference in colour can be attributed to the corrosion in the galvanised steel tanks. Mn, Fe, and SO_4^{2-} did not differ significantly between the different tank materials. However, it can be noted that among the three tank materials, water from galvanised steel tanks had the highest levels (for all five physicochemical parameters, except SO_4^{2-}) followed by plastic tanks, and lastly stainless steel tanks (Table 3). Our results suggest that stainless steel tanks perform better in maintaining water quality compared with plastic tanks and galvanised steel tanks.

Effect of tank age on water quality

The bacteriological and physicochemical analyses of water samples with regard to tank age on quality are presented in Table 4. The tank age was found to have a significant effect on the quality of water flowing from the storage tank, which is contrary to the findings of Schafer & Mihelcic (2012). Faecal coliforms ($p = 0.026$) as well as total coliforms ($p = 0.020$) were significantly higher in water flowing from older tanks compared with that from newer tanks. We observed that faecal coliforms were, on average, absent in water from tanks of 0–5 years old, but were present (mean value = 1 CFU/100 ml) in that from tanks of 6–10 years old and ≥10 years old as shown in Table 4.

Total coliforms were lowest in water in tanks of 0–5 years old (mean = 12 CFU/100 ml), higher in water in tanks of 6–10 years old (mean = 17 CFU/100 ml), and highest in water in tanks >10 years old (mean = 255 CFU/100 ml). Similarly, Mn and Fe followed the same pattern as described above. This effect could have been due to the varying deterioration of the physical conditions of the storage tanks, for example, the surfaces of the old tanks were more corroded than those of the new tanks. Deterioration of water quality increases with age of the tanks as the tank materials leach constituents and corrosions in stored water over time (Committee 2020); and such constituents encourage the growth of certain bacteria. Deterioration of the

Table 3 | The physicochemical parameters of water flowing from storage tanks of different material types

Parameter	**Mean**			
Tank material	**SS ($n = 24$)**	**PE ($n = 58$)**	**GS ($n = 30$)**	**SIG. ($\alpha = 0.05$)**
Free chlorine (mg/L)	0.004 ± 0.001	0.006 ± 0.001	0.042 ± 0.040	0.952
Colour (Pt Co)	6.250 ± 0.620	9.020 ± 0.920	17.430 ± 3.500	*0.018
SO_4^{2-} (mg/L)	6.650 ± 0.160	5.890 ± 0.300	6.000 ± 0.370	0.549
Mn (mg/L)	0.011 ± 0.001	0.013 ± 0.001	0.018 ± 0.001	0.089
Fe (mg/L)	0.027 ± 0.001	0.055 ± 0.020	0.207 ± 0.080	0.242

SS = stainless steel tanks; PE = plastic tanks; GS = galvanised steel tanks; *, significance ($\alpha = 0.05$).

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Table 4 | Bacteriological and physicochemical parameters of water flowing from tanks of different ages

Parameter **Tank age in years**	**Mean** **0–5 (*n* = 43)**	 **6–10 (*n* = 22)**	 **>10 (*n* = 47)**	**SIG. ($\alpha = 0.05$)**
Bacteriological analysis				
Total coliforms (CFU/100 ml)	12 ± 3	17 ± 5	26 ± 4	*0.020
Faecal coliforms (CFU/100 ml)	0	1	1 ± 1	*0.026
Heterotrophic bacteria (CFU/100 ml)	491 ± 97	919 ± 340	964 ± 172	0.060
Physicochemical analysis				
Free chlorine (mg/L)	0.010 ± 0.001	0.010 ± 0.001	0.030 ± 0.002	0.580
Colour (Pt Co)	7.530 ± 0.740	8.140 ± 1.230	14.740 ± 2.430	0.120
SO_4^{2-} (mg/L)	6.66 ± 0.200	5.110 ± 0.540	5.990 ± 0.300	*0.042
Mn (mg/L)	0.009 ± 0.001	0.010 ± 0.001	0.020 ± 0.001	*<0.001
Fe (mg/L)	0.002 ± 0.001	0.020 ± 0.001	0.140 ± 0.060	*<0.001

*, significance ($\alpha = 0.05$).

physical conditions of tanks can be reduced through routine maintenance of the tanks. However, we observed a poor maintenance culture in the study communities; with only eight households (16%) reported to have carried out routine maintenance works on their tanks (maintenance works, in this case, includes major tasks such as repainting tanks, changing the pipe fittings and connectors on the tanks, etc.). It is important to note that the deterioration of certain tank types, particularly plastic tanks, may be difficult to control because of the nature of the material itself. For instance, meanwhile, steel tanks can be repainted to prevent corrosion, it is not possible to paint plastic tanks to protect them from changing their chemical compositions as a result of much exposure to extreme sunlight. This means over time as the tanks age, they lose some of the properties meant to preserve good water quality., In our study, colour of stored water, and SO_4^{2-} in the stored water were not significantly affected by tank age. However, the effect of tank age on colour and SO_4^{2-} in the stored water is still not well understood and, therefore, further research is required to systematically examine how tank age affects the evolution of SO_4^{2-} compounds and colour in stored water.

Effect of tank connectors on water quality

Tank connectors are fittings installed on tanks to connect pipes for outlets, inlets, overflow, and washouts. Two types of the tank connectors were observed during the study and these were GI connectors, and polypropylene random copolymer (PPR)

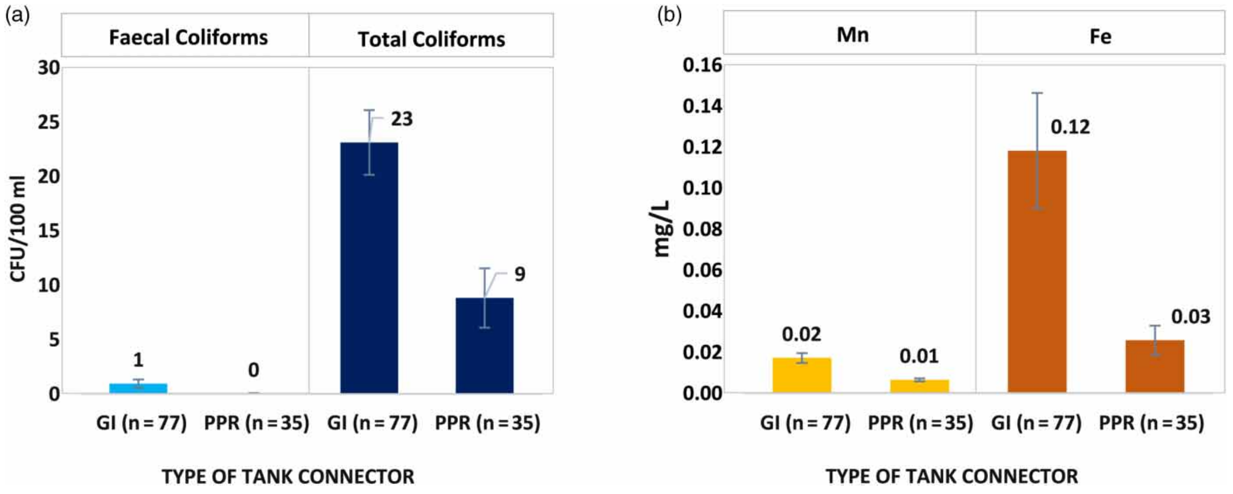

Figure 3 | Quality of water flowing from storage tanks with different connectors (i.e., galvanised iron (GI) and polypropylene random copolymer (PPR) tank connectors); (a) faecal coliforms and total coliforms; (b) manganese (Mn) and Iron (Fe). Error bars represent the standard error around the mean values. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2021.411.

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connectors. It was found that 31% of the tanks had PPR connectors while the remaining 69% had GI connectors. PPR connectors were common in new tank installation, while GI connectors were mainly used in old tank installations. The use of the connectors did not depend on the type of tank material, for instance, many plastic tanks were fitted with GI connectors, while some stainless steel tanks had PPR connectors. The analysis of microbiological indicators revealed significantly higher contamination of water stored or flowing from tanks with GI fittings compared with those with PPR fittings. As shown in Figure 3, faecal coliforms were significantly higher ($p = 0.035$) in water flowing from tanks with GI connectors (mean value 1 CFU/100 ml) compared with that flowing from tanks with PPR connectors that on average did not contain any faecal coliforms.

Similarly, total coliforms and HPC averaged 9 CFU/100 ml and 360 CFU/100 ml, respectively, in water from tanks with PPR connectors but were significantly higher ($p = 0.008$ and 0.002 respectively) in that from tanks with GI connectors (mean value = 23 and 962 CFU/100 ml respectively). Mn and Fe levels were also significantly higher in water from tanks with GI connectors ($p = 0.001$).

The effect of GI connectors on water quality was similar to the effect of GS tanks on water quality because of corrosion, a phenomenon that has been reported (Lemon 2020) to favour bacteria growth. The corrosion of GI connectors clearly stood out in stainless steel tanks that had them; with the tank surfaces appearing smooth and clean, while the area around the inlets, outlets, and washouts appeared clogged with corrosion deposits. This was even worse in old plastic tanks (i.e., ≥10 years old). The surfaces of some of them (originally white in colour) had turned brownish (see Figure 4). It was observed that tanks that had PPR connectors generally had much cleaner water compared with those with GI connectors.

Effect of hydraulic retention time on water quality

Table 5 presents the hydraulic retention time and quality of water flowing from the water storage tanks. The result show that water quality deteriorated over time while being stored. This is in line with the results of earlier studies such as Al-Bahry *et al.* (2013) and Nnaji *et al.* (2019).

In addition, the analysis showed that faecal coliforms were present in water stored in the tank for about 2 days and 3 or more days (mean = 1 CFU/100 ml) but absent in water stored for a day or less. However, the differences were not statistically significant. A similar pattern was observed for total coliforms, with an average value of 13 CFU/100 ml for 1 day of retention time, 19 CFU/100 ml for 2 days, and 22 CFU/100 ml for 3 or more days of hydraulic retention time.

Similar observations were made in previous studies such as Evison & Sunna (2001), in which heterotrophic bacteria count increased from 1.7 log to 5.2 and log 7.2 after water was stored for four and seven days, respectively. A study by WHO (2002)

Figure 4 | Corrosion deposits in a plastic tank with galvanised iron connectors.

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Table 5 | Bacteriological and physicochemical parameters of water from storage tanks with different hydraulic retention time

Parameter **Residence time**	**Mean** $\leq$**1 day (*n* = 32)**	 **2 days (*n* = 34)**	 $\geq$**3 days (*n* = 46)**	**SIG. ($\alpha = 0.05$)**
Bacteriological analysis				
Total coliforms (CFU/100 ml)	13 ± 4	19 ± 4	22 ± 4	0.344
Faecal coliforms (CFU/100 ml)	0	1	1 ± 1	0.254
Heterotrophic bacteria (CFU/100 ml)	687 ± 189	585 ± 114	967 ± 201	0.277
Physicochemical analysis				
Free chlorine (mg/L)	0.04 ± 0.03	0.00	0.010 ± 0.001	0.339
Colour (Pt Co)	7.13 ± 1.00	7.97 ± 0.93	15.15 ± 2.42	0.008
SO_4^{2-} (mg/L)	6.37 ± 0.27	6.45 ± 0.34	5.61 ± 0.32	0.072
Mn (mg/L)	0.010 ± 0.001	0.004 ± 0.001	0.004 ± 0.001	0.458
Fe (mg/L)	0.040 ± 0.001	0.030 ± 0.01	0.120 ± 0.001	0.085

also reported the occurrence of elevated HPC in stagnant parts of piped distribution systems such as storage tanks under the indirect cold water supply system. As recommended by both local and international (WHO) standards, a residual free chlorine concentration of 0.2–0.5 mg/L should be sufficient to maintain the quality of water received by households. However, the rapidly declining concentration of the residual free chlorine in storage tank water implies that this level of disinfection is not sufficient to maintain good water quality during storage. A similar observation was made by US CDC (2020). A solution to this would be the disinfection of tank water at the household level. However, this was found to be a rare practice; only seven (6%) households reported disinfection of their tank water. Moreover, this was done only after cleaning. Our study suggests there should be an increase in the chlorine dosage during treatment by the responsible municipal authorities, as this would reduce the regrowth of bacteria in household water storage tanks, and consequently (reduce) transmission of waterborne diseases.

Effect of tank cleaning on water quality

Only 40% of the surveyed households had reported to have cleaned their water storage tanks in the past. The main reason (as reported by 55% of the households that cleaned their tanks) was because of changes in the physical properties of water; colour, taste, and odour from the storage tanks. The results of the bacteriological and physicochemical parameters of water from storage tanks with different cleaning frequencies are presented in Table 6.

Table 6 | The bacteriological and physicochemical parameters of water from storage tank with different periods between tank cleaning

Parameter **Period since last cleaning (months)**	**Mean** **<11 (*n* = 20)**	 **12–23 (*n* = 20)**	 $\geq$**24 (*n* = 72)**	**SIG. ($\alpha = 0.05$)**
Bacteriological analysis				
Faecal coliforms (CFU/100 ml)	0	2 ± 1	0	0.169
Total coliforms (CFU/100 ml)	25 ± 6	26 ± 5	15 ± 3	0.013
Heterotrophic bacteria (CFU/100 ml)	770 ± 132	616 ± 132	814 ± 154	0.178
Physicochemical analysis				
Free chlorine (mg/L)	0.01 ± 0.001	0.01 ± 0.001	0.02 ± 0.001	0.979
Colour (Pt Co)	9.6 ± 1.19	14.6 ± 3.08	9.89 ± 1.47	0.083
SO_4^{2-} (mg/L)	5.22 ± 0.47	6.34 ± 0.60	6.23 ± 0.19	0.057
Mn (mg/L)	0.020 ± 0.001	0.020 ± 0.010	0.010 ± 0.001	0.138
Fe (mg/L)	0.050 ± 0.001	0.100 ± 0.050	0.100 ± 0.040	0.273

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Surprisingly, cleaning was found to have a reverse effect on the water quality. Higher faecal coliforms and total coliforms were recorded in water from tanks that had been cleaned more recently compared with those that were last cleaned longer time or those that have never been cleaned before since installation. This finding contradicts that of previous research such as Akuffo *et al.* (2013) and Nnaji *et al.* (2019). In the latter study, a significant reduction in total coliform counts was attributed to cleaning. The cause of this contradictory finding could probably be due to improper cleaning of the tanks resulting from flawed designs and improper installation of the storage tanks. Firstly, the design of the tanks did not allow for installation of outlets and washouts in positions that could allow for complete emptying of tanks. As shown in Figure 5, outlets and washouts were installed off the bottom of tanks, following marks placed on the tanks by the manufacturers.

Secondly, many of the tanks did not have washouts installed. This means that sediments that settled at the bottom of the tanks remained trapped there. The problem was further compounded by the manner in which the tanks were installed; many of which did not allow for the tanks to easily be disconnected and carried down for proper cleaning because of narrow supports/bases (see Figure 5(a)). This means sediments at the bottom of tanks and dirt that got dislodged when scrubbing the tank surfaces had no means of being fully removed from the tanks neither through washouts and outlets nor by disconnecting and carrying down the tanks, but instead became resuspended in the tank water when refilling after cleaning, causing more contamination. It was further noted that households did not have standard procedures of cleaning the storage tanks.

Binary logistic regression model for predicting water quality

As demonstrated in the earlier sections, only faecal coliforms, total coliforms, heterotrophic bacteria, free chlorine, colour, SO_4^{2-}, Mn and Fe were significantly affected by storage tanks. Further analyses revealed that hydraulic retention time did not significantly affect any of the above-mentioned water quality parameters, while tank cleaning had a reverse effect on water quality. This left tank age, tank material, and tank connectors as the only predictors of water quality in storage tanks. Of the above eight water quality parameters that were significantly affected by the storage tanks, bacteriological parameters were considered for the model because they are regarded by most standards as the main water quality indicators, since they pose greater health risks to humans compared with the physicochemical parameters. Out of the three bacteriological parameters, total coliforms was selected as the dependent variable to be predicted because although faecal coliforms was also an alternative, it was present in only 12% of the tanks, thereby making total coliforms more suitable for modelling. HPC was not considered for modelling because previous reports appeared to suggest that it is generally not well understood. In fact, there are no recommended standards for it in Uganda. Binary logistic regression model was therefore carried out with tank age, tank material and tank connectors used to predict the presence of total coliforms in tank water. Water quality can either be acceptable or unacceptable depending on whether total coliforms is absent or present.

Figure 5 | The manner in which many tanks were installed: (a) a narrow support/tank base; (b) outlet installed off the bottom of the tank; (c) washout installed off the bottom of the tank. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2021.411.

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Table 7 | Binary logistic regression model showing prediction of total coliforms by tank features

Predictor Variables		**B**	**S.E.**	**Sig.**	**Exp(B)**	**95% C.I. for Exp(B)**	
Tank type/material	Stainless steel tanks	−1.171	0.793	0.140	0.310	0.066	1.466
	Plastic tanks	−1.003	0.680	0.140	0.367	0.097	1.391
Tank connector	PPR connectors	−0.049	0.550	0.929	0.952	0.324	2.799
Tank age	Tank age 0 to 5 years	0.049	0.691	0.944	1.050	0.271	4.069
	Tank age 6 to 10 years	−0.133	0.676	0.845	0.876	0.233	3.296
	Constant	1.473	1.318	0.264	4.363		
	Nagelkerke R Square = 0.063						
	Galvanised steel tanks, GI connectors, and tank age over 10 years were taken as the constant against which the other categories of the predictor variables were compared						

Note: B, Intercept; S.E. Standard Error; Exp(B), Odds ratio.

As shown in Table 7, the odds $p = 0.008$ and $p = 0.002$, respectively, of stored water getting contaminated with total coliforms was much lower in stainless steel tanks: 0.310 (95% CI: 0.066, 1.466); and plastic tanks: 0.367 (95% CI: 0.097, 1.391) when compared with galvanised steel tanks, taking into consideration the age of tanks and type of connectors used. However, the difference was not statistically significant at 95% C.I. Conversely, the odds of having total coliforms present in tanks was nearly the same; 0.952 (95% CI: 0.324, 2.799) whether PPR or GI connectors are used. This suggests that when other variables are taken into consideration, the type of tank connectors used does not have much effect on the presence of total coliforms in storage tanks ($p = 0.929$). The model further revealed that the odds of having total coliforms present in tanks of 0 to 5 years; 1.050 (95% CI:0.271, 4.069) and 6 to 10 years; 0.876 (95% CI: 0.233, 3.296) were not much different when compared with tanks more than 10 years old. This means that tank age is not a strong predictor of the presence of total coliforms when tank type and connectors are also considered ($p = 0.944$ and $p = 0.845$). This model therefore implied that, although not statistically significant ($p = 0.140$), tank type/material is the strongest predictor of total coliform presence in water tanks, taking into consideration the age of the tank and type of connector used. The odds of household water becoming contaminated during storage in the stainless steel tanks (first) and plastic tanks (second) are relatively low, and therefore water flowing from such tanks is relatively safer than that from galvanised steel tanks.

CONCLUSIONS

Notwithstanding its importance in providing households with a regular supply of water, indirect cold water supply systems compromise water quality. This study investigated the effects of storage tank features and cleaning practices on water quality. Our study concluded that tank features had a significant effect on the stored water quality, with tank types having the greatest impact on water quality. Galvanised steel tanks were associated with the highest levels of water contamination, followed by plastic tanks and lastly stainless steel tanks with lowest levels of water contamination. The type of tank connectors and tank age did not have a significant effect on the water quality when the tank material was considered. Water quality deteriorated over time water was stored in the tanks. The study further concluded that tank cleaning did not guarantee improvement of water quality, if not properly carried out using the correct cleaning methods and tools, as wrong cleaning methods and tools were found to lead to contamination of tank water.

Our study findings recommend: periodic cleaning of the water storage tanks under indirect cold water supply but using correct cleaning methods, materials and tools; replacement of the existing galvanised steel tanks with stainless steel tanks, and GI tank connectors with PPR tank connectors to reduce contamination of stored water; (re)-installation of tank washouts at correct positions, preferably at the tank bottom to allow for complete emptying of the tanks during cleaning.

The study findings suggest that, apart from the factors examined in current study, there were other factors that significantly affected the water quality under the indirect cold water supply system. Therefore, further research is required to investigate the whole indirect water supply system, including features such as the piping system. In addition, further research is recommended in order to determine an optimal cleaning frequency.

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AUTHORS' CONTRIBUTIONS

Conceptualisation, MM; Research design, MM, LOO, TGN, NK, IN, AOP, NH, and EK; Data collection and analysis, MM, LOO and TGN; Writing – original draft preparation, MM, LOO, and TGN; Writing – review and editing, MM, NK, AOP, LOO, TGN, NH, EK; Visualisation, LOO; Supervision, MM; Project administration, NK and MM; Funding acquisition, MM. All authors have read and agreed to the published version of the manuscript.

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DATA AVAILABILITY STATEMENT

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

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