



Development and appraisal of handwash-wastewater treatment system for water recycling as a resilient response to COVID-19

Peter Wilberforce Olupot^a, Emmanuel Menya^{b,*}, Joseph Jjagwe^a, Joel Wakatuntu^a,
Tonny Kavuma^a, Andrew Wabwire^a, Steven Kavuma^d, Samuel Okodi Mcmondo^d,
Betty Nabuuma^a, Herbert Mpagi Kalibbala^c

^a Department of Mechanical Engineering, College of Engineering, Design, Art and Technology, Makerere University, P.O. Box 7062, Kampala, Uganda

^b Department of Biosystems Engineering, Gulu University, P.O. Box 166, Gulu, Uganda

^c Department of Civil and Environmental Engineering, College of Engineering, Design, Art and Technology, Makerere University, P.O. Box 7062, Kampala, Uganda

^d Lunwero Industries Limited, P.O. Box 1651, Kampala, Uganda

ARTICLE INFO

Editor: Dr. G.L. Dotto

Keywords:

Handwashing
Wastewater treatment
Sand
Zeolite
Granular activated carbon
COVID-19

ABSTRACT

In this work, results from characterization of handwashing wastewater from selected stations in Kampala City, Uganda, revealed that handwashing wastewater did not meet permissible international standards for wastewater discharge to the environment. The ratio of BOD₅ to COD of < 0.5 implied that handwashing wastewater was not amenable to biological treatment processes. Turbidity of > 50 NTU pointed to the need for a roughing filter prior to slow sand filtration. Subsequently, a handwashing wastewater treatment system consisting of selected particle sizes of silica sand, zeolite, and granular activated carbon as filtration and/or adsorption media was developed and assessed for performance towards amelioration of the physicochemical and biological parameters of the handwashing wastewater. Treated water from the developed wastewater treatment system exhibited a turbidity of 5 NTU, true color of 10 Pt-Co, apparent color of 6 Pt-Co, and TSS of 9 mgL⁻¹, translating to removal efficiencies of up to 98.5%, 98.1%, 99.7%, and 96.9%, respectively. The residual total coliforms and *E. coli* of 1395 and 1180 CFU(100 mL)⁻¹ respectively, were totally eliminated upon disinfection with 0.5 mL NaOCl (3.5% wt/vol) per liter of treated wastewater. The treated water was thus suitable for recycling for handwashing purpose as opposed to letting handwashing wastewater merely go down the drain. This approach provides a resilient response to COVID-19, where communities faced with water scarcity can treat and recycle handwashing wastewater at the point of washing. It thus enables more people to have the opportunity to practice handwashing, abating the high risks of infection, which could otherwise arise.

1. Introduction

Coronavirus disease 2019 (COVID-19) is an infectious disease caused by the novel coronavirus now called severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The disease was declared a global pandemic on the 11th March, 2020 by the World Health Organization (WHO) [1]. It is mainly spread through human to human transmission. This mode of transmission prompted several nations, including Uganda, to take bolder steps aimed at curbing its rapid spread. Such steps include closure of the country's borders, social distancing, implementation of lockdowns, ban on public gatherings, closure of schools and places of public religious worship, suspension of a huge section of public and private transport, use of face masks, as well as extensive promotion of

handwashing with soap and clean water, among others. The latter option has been widely recommended by WHO [2] as one of the most effective ways for curbing the spread of COVID-19. However, due to water scarcity coupled with the lack of clean safe water, some communities in Uganda do not have the opportunity to effectively practice handwashing, exposing them to high risks of catching COVID-19, as well as other illnesses [3]. This scenario disproportionately affects the poor, refugees, and displaced persons who live in crowded settlements with often limited or no existing water infrastructure [4,5]. For instance, during times of water scarcity, 85% of rural dwellers spend more than an hour fetching water for various applications [6]. For such communities, using their painstakingly acquired water on handwashing may be looked at as a luxurious act. This in turn negates the beneficial effect of

* Corresponding author.

E-mail address: E.menya@gu.ac.ug (E. Menya).

<https://doi.org/10.1016/j.jece.2021.106113>

Received 26 March 2021; Received in revised form 15 July 2021; Accepted 22 July 2021

Available online 28 July 2021

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handwashing in curbing the spread of COVID-19, as well as other illnesses.

The Government of Uganda, its developmental partners, and the civil society organizations have made effort towards addressing the problem of water scarcity and the lack of clean safe water in the country. For instance, through the National Water and Sewerage Corporation (NWSC), the government is extending piped water to its small urban centers. Consequently, piped water infrastructure currently serves 20% of the country's population with increased access in the rural areas [7]. The remaining majority of the population in the country relies on improved groundwater point sources such as boreholes (31%), protected dug wells (16%), and protected springs (15%), while a small population still relies on surface water [8]. In spite of these significant efforts by government, 58% of households in the country still use unsafe sources contaminated with fecal matter [8]. Due to some of these challenges, 92% of the already few available sanitation facilities with handwashing stations do not use clean water and soap [9]. This poses high risks of infection, for instance, through hand-to-mouth contacts. Moreover, after handwashing, the generated wastewater is usually openly discarded untreated to the immediate surroundings, while in a few instances, to the sewer systems. This practice is not only wasteful but also paves way for secondary sources of the coronavirus, as well as other pathogens. A case in point is the SARS-CoV-2 ribonucleic acid (RNA) detected in the untreated wastewater in Australia [10], Netherlands [11], Paris [12], and North America [13]. These findings underscore the need for treatment of the handwashing wastewater prior to its discharge to the environment.

The treated handwashing wastewater could also be recycled, making it possible for more users to practice handwashing. There are some guidelines regarding the quality of water desired for handwashing. For instance, the risk-based guidelines developed by Verbyla et al. [14] suggest that water containing < 1000 *Escherichia coli* (*E. coli*) colony-forming units (CFU) per 100 mL is capable of removing *E. coli* from hands with a probability > 99.9%, provided handwashing is done correctly with soap and with the correct technique. WHO [15] also recommends that the quality of water does not necessarily need to meet drinking-water standards to allow effective removal of pathogens from hands. However, for purposes of reducing the risks of infection from hand-to-mouth contacts, effort needs to be made to use water of the highest quality possible for handwashing [14,15].

There are currently few research attempts that have been made towards treatment of wastewater generated from handwashing for potential recycling and reuse. For instance, Nguyen et al. [16] employed a biologically activated membrane bioreactor (BAMBi) to treat wastewater generated from handwashing and other sources such as personal hygiene and toilet flushing system for potential recycling and reuse. Elsewhere, Ziemba et al. [17] studied the aspects of nutrient-balancing in handwashing wastewater for enhanced biological treatment in a BAMBi system, where the treated water could then be recycled and reused. Other related studies focus on onsite gray water treatment for potential recycling and reuse [18–20]. However, unlike in the studies where a BAMBi system was employed to treat wastewater for potential recycling and reuse in various applications, in this study, wastewater from handwashing is treated using silica sand, zeolite, and granular activated carbon (GAC) as filtration and/or adsorption media that can be locally sourced in many developing countries.

Essentially, slow sand filters remove contaminants from water by physical, chemical, and biological processes. For instance, in the physical process, the inert suspended particles are physically strained out as water enters the top layer of the sand bed. In the biological process, the biofilm (or *schmutzdecke*) formed at the sand-water interface contains microbial communities which break down various nutrients and carbonaceous materials, while the predatory bacteria which form majority of the microbial communities present in the biofilm feed on the pathogens passing through the filter [21]. Moreover, as water seeps downward through the sand bed, the biofilm also strains out some of the

particulate matter present in water [22]. If the influent turbidity is > 50 NTU, then roughing filtration is carried out prior to slow sand filtration [23]. This prevents frequent clogging of the sand filter. Zeolite and GAC are then employed as post filtration media to adsorb pollutants such as humic substances not effectively removed via slow sand filtration [24, 25]. Such pollutants are removed through adsorption onto the media's external surface [26], physical filtration [27], as well as through biodegradation of the biodegradable component upon formation of an active biofilm on the filter bed [27].

In this study, silica sand, zeolite, and GAC were milled and configured to treat handwashing wastewater for potential recycling in handwashing as a resilient response to COVID-19. Samples of raw water employed for handwashing at selected public facilities, as well as the resultant wastewater were characterized for pH, turbidity, total suspended solids (TSS), total dissolved solids (TDS), true color, nitrates, ammonia-nitrogen, total phosphorous, biological oxygen demand (BOD₅), chemical oxygen demand (COD), total coliforms, and *E. coli*. The results from the characterization studies helped to ascertain compliance of the raw water and handwashing wastewater with existing national and/or international regulations, as well as informed the design choices for the appropriate wastewater treatment systems. This study contributes to the growing body of literature on resilient responses to the COVID-19 pandemic.

2. Materials and methods

2.1. Raw water and wastewater collection

Raw water and wastewater samples were collected from selected handwashing stations installed at public facilities in Kampala, Uganda. The public facilities included *F*, *Q*, *N*, *W*, and *K*, where *F* was a pharmaceutical retail outlet, *Q* was a supermarket, *W* and *K* were fresh food markets, and *N* was a commuter taxi park. These facilities were selected for study because of the diverse and concentrated human activities associated with the facilities, making them potential COVID-19 hotspots.

2.2. Raw water and wastewater characterization

The collected raw water samples, as well as samples of the wastewater generated from handwashing were characterized for physico-chemical parameters at Makerere University's Public Health and Environmental Engineering Laboratory in Kampala. The physico-chemical parameters included pH, turbidity, TSS, TDS, nitrates, ammonia-nitrogen, total phosphorous, COD, BOD₅, true color, total coliforms, and *E. coli*. The description of each of the methods followed to determine each of the parameters is given below:

2.2.1. pH, true color, turbidity, and TSS

The pH of the raw water and wastewater was determined using a portable meter (HQ 30d Flexi). The true color was determined by filtering the water through a Whatman filter (GF/C 47 mm diameter, 1.2 μm pore size), and subsequently employing the platinum cobalt standard method to analyze the filtered water for true color [28]. The turbidity of the water was determined following the absorbptometric method 8237, where measurements were made at 450 nm wavelength using a spectrophotometer (HACH DR 2000). TSS was measured using a spectrophotometer in accordance with the HACH standard: Photometric Method 8006 [28].

2.2.2. TDS

TDS was determined by filtering 100 mL of water sample through a 0.45 μm glass fiber filter. The filtrate was subsequently transferred into a pre-weighed beaker where it was evaporated to dryness in an oven for 24 h at 105 °C. The residue was then dried at 180 °C for 2 h, cooled in a desiccator, and immediately weighed. The TDS was subsequently

determined as the mass of solid normalized to the volume of water filtered [28].

2.2.3. Nitrates, ammonia nitrogen, and total phosphorous

The amount of nitrates (NO_3) present in the water samples was determined by employing cadmium to reduce the nitrate to nitrite, followed by colometric determination of the nitrite content in the water samples [28]. The nitrate content was subsequently obtained after correcting for any nitrite that was present in the samples. The amount of ammonia nitrogen present in the water samples was determined based on the direct nesslerization method, while the total phosphorous content was determined based on the persulfate digestion, followed by the ascorbic acid spectrophotometric method [28].

2.2.4. BOD₅

The BOD₅ of wastewater was determined based on the BOD track method [28]. This method involved seeding the wastewater sample in 300 mL incubation bottles with microorganisms, followed by determination of the initial dissolved oxygen (DO) concentration in the wastewater sample. The incubation bottles with the wastewater sample were then sealed, and incubated in the dark at 20 °C for 5 days, followed by determination of the final DO concentration of the wastewater sample. Incubation in the dark was purposely to prevent the production of DO via photosynthesis, which would otherwise interfere with the experimental results. The difference between the initial and final DO readings was determined, and subsequently corrected for BOD₅ of the seed and dilution factor. The corrected value was obtained as the BOD₅ of the wastewater.

2.2.5. COD

The COD of the wastewater was determined based on the closed reflux colometric method [28]. In this method, a 50 mL sample of wastewater in a refluxing flask was diluted with distilled water up to the 50 mL mark, followed by addition of 1 g of mercury sulfate (HgSO_4), a few glass beads, and 5 mL of sulfuric acid reagent. The resultant contents in the refluxing flask were subsequently mixed, and later allowed to cool. 25 mL of 0.0417 M $\text{K}_2\text{Cr}_2\text{O}_7$ solution was then added to the cooled solution, followed by mixing. The refluxing flask with its contents was subsequently connected to the condenser, and the cooling water turned on. Via the open end of the condenser, 70 mL of sulfuric acid was added to the contents in the refluxing flask with swirling and mixing. After 2 h of refluxing, and after the contents had sufficiently cooled, the condenser was washed down with distilled water, doubling the volume of the contents in the flask, which were subsequently allowed to cool. Two drops of Ferroin indicator were then added to the contents in the refluxing flask. The residual $\text{K}_2\text{Cr}_2\text{O}_7$ was titrated with ferrous ammonium sulfate (FAS) until the color of the contents changed from bluish green to reddish brown. A distilled water blank was subsequently refluxed and titrated with the reagents. COD was then calculated according to Eq. (1).

$$\text{COD} = \frac{\text{Molarity of FAS} \times (\text{FAS}_{\text{blank}} - \text{FAS}_{\text{sample}})}{\text{volume of sample}} \times 8000 \quad (1)$$

2.2.6. Total coliforms and *E. coli*

The total coliforms and *E. coli* were determined based on the spread plate method, where the water sample was spread evenly on an agar media, incubated at 37 °C for 18–24 h [28]. The total number of bacteria (CFU/100 mL) was then calculated. The *E. coli* parameter was employed as a conservative indicator for the presence of potentially harmful pathogen in the water samples [29].

2.3. Collection and preparation of the filter media materials

Silica sand, zeolite, and granular activated carbon (GAC) were selected as filter media materials due to their ability to adsorb and filter

out contaminants from water. Silica sand was procured from Entebbe sand mines located in Wakiso district in Uganda. To obtain pure samples, the as-received sand was water-washed, removing any contaminants such as organic matter present in the sand. The water-washed sand was subsequently oven-dried at 105 °C for 24 h, followed by crushing using a mallet hammer, a mortar and pestle, as well as using a ball mill. The crushed sand was finally sieved to obtain particle sizes of 6.00, 2.36, 1.00, 0.60, and 0.30 mm. The obtained samples were each stored in polythene bags to avoid any potential contamination from dust.

Zeolite rocks were collected from the mines of Mount Elgon located in Mbale city in Uganda. These were crushed using a mallet hammer, a mortar and pestle, as well as using a ball mill. The crushed zeolite was then sieved to obtain particle sizes of 6.00, 2.36, 1.00, 0.60, 0.30, and 0.21 mm. Each of the prepared samples were water-washed to remove any contaminants present in the zeolite. The water-washed samples were then oven-dried at 105 °C for 12 h, and subsequently stored in polythene bags to avoid the possibility of contamination from dust.

The GAC (Jacobi Aquasorb CS Activated Carbon) was procured from Davis and Shirtliff company located in Kampala city in Uganda. From the manufacturer's specifications, the procured activated carbon had a typical particle size range of 3.35–1.70 mm, specific surface area of 1050 m^2g^{-1} , and a particle density of 540 gm^{-3} . Similar to silica sand and zeolite, the as-received activated carbon was also crushed and sieved to obtain particle sizes of 6.00, 2.36, 1.00, 0.60, and 0.30 mm. Each of the prepared samples were water-washed to remove any contaminants present in the activated carbon. The water-washed samples were then oven-dried at 105 °C for 12 h, and subsequently stored in polythene bags to avoid the possibility of contamination from dust.

2.4. Characterization of the filter media materials

2.4.1. X-ray fluorescence (XRF) spectroscopy

For purposes of characterization, each of the samples of silica sand and zeolite were initially pulverized into powder using a Hazorg mill. 1 g of each of the prepared powdered sample was then mixed with 7 g of lithium bromide (LiBr) in a gold platinum mold and subsequently burnt on an X-ray fluorescence (XRF) bead maker at 750 °C using oxygen and liquid petroleum gases. The resultant sample was cooled and subsequently placed in an XRF cassette for analysis using their different material calibrations. Loss on ignition (LOI) for each of the samples of silica sand and zeolite was determined by burning 2 g of the sample in a muffle furnace at temperature of 950 °C.

2.4.2. Fourier transform infra-red (FTIR) spectroscopy

FTIR spectroscopy was employed to determine the surface functional groups present on the surface of each of the filter media materials. This involved clamping each of media sample materials on the probe, and the respective spectra subsequently obtained by scanning in the range of 4000–400 cm^{-1} .

2.4.3. Scanning electron microscopy (SEM)

The morphology of the different filter media materials was examined under the field emission scanning electron microscope (Tescan Vega 3, Pleasanton, USA). Each of the filter media materials were fixed on double sided adhesive carbon tape, vacuum dried, and then scanned at an acceleration voltage of 10 kV.

2.5. Construction of the filtration column

The filtration column was constructed from a polyvinyl chloride (PVC) tube with internal diameter and height of 100 and 300 mm, respectively. The bottom of the tube was fitted with a perforated perspex plate to hold the filtration media, while the threaded rods were fitted through the flange to serve as stands for the filtration column (see Fig. 1). The joints of the resultant filtration column were sealed using araldite adhesive.

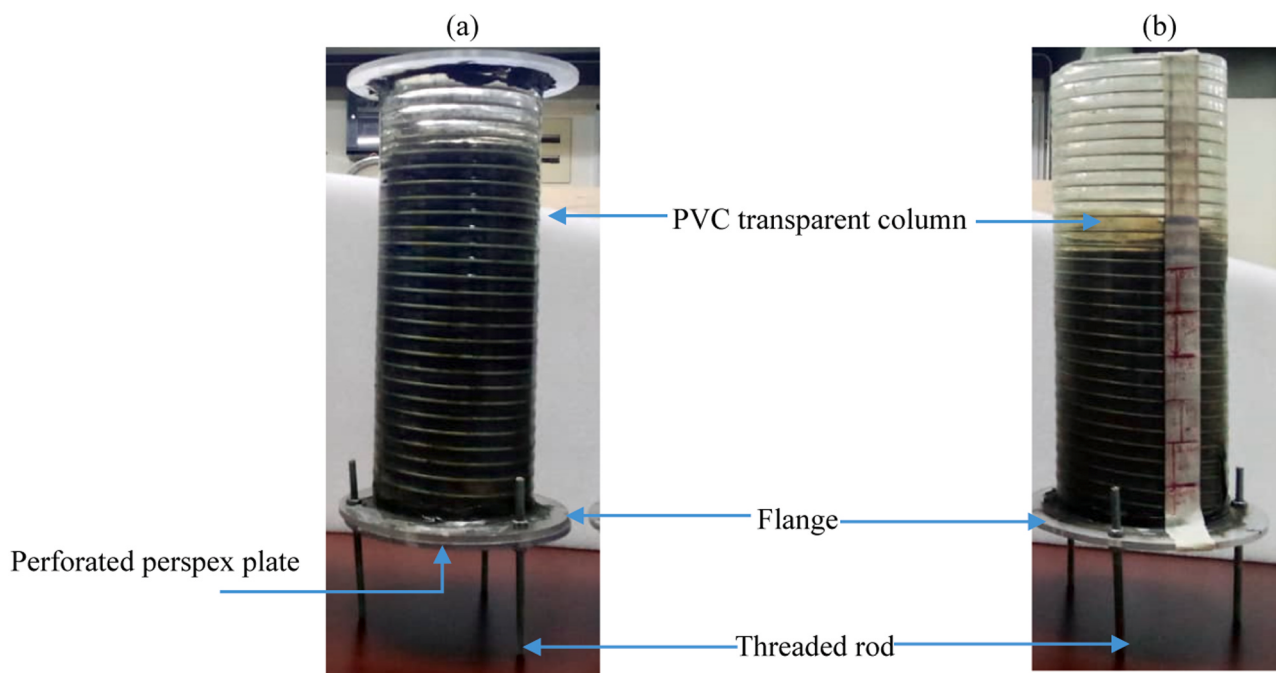


Fig. 1. Photographs of some of the constructed filtration columns with zeolite (a) and GAC (b) filter media.

2.6. Performance evaluation of the constructed wastewater treatment system

2.6.1. Performance of the individual filtration units

Silica sand, zeolite, and GAC of different particle sizes were each separately packed in the constructed columns to different depths (see Fig. 2). The packed filter columns were each subsequently investigated to arrive at bed depths, flowrates, and contact times that result in the highest removal of turbidity, color, and TSS from handwashing wastewater. To achieve this, a peristaltic pump was employed to pump 1 L of handwashing wastewater through each separately packed filter column at a rate of 0.5 L min^{-1} , with a diffuser plate placed 2 cm above the standing head. The diffuser plate enabled homogeneous supply of wastewater through the packed filter column. In addition, due to high turbidity of the handwashing wastewater ($> 50 \text{ NTU}$), a roughing filter was also constructed from silica sand of different particle sizes (Fig. 2a), and subsequently investigated for performance towards removal of turbidity, color, and TSS from the handwashing wastewater. At the bottom of the roughing filter, a muslin cloth was employed to avoid the undesired release of suspended particles to the subsequent filter media, which would otherwise influence its performance. The filtrate was obtained from the bottom of each packed filter column, and subsequently analyzed for turbidity, true color, apparent color, and for TSS to ascertain the removal efficiency due to each packed filter column.

2.6.2. Performance of the combined filtration units

The optimized configurations due to each filter media, as well as the roughing filter obtained in Section 2.5.1 were carefully integrated into a single filter column/or treatment system, and subsequently assessed for overall performance towards removal of turbidity, color, and TSS from the handwashing wastewater. The filtrate from the configuration that performed best in removing the above mentioned physio-chemical parameters was further assessed for presence of *E. coli* and total coliforms to establish its safety for handwashing. In case of presence of pathogens, a number of experimental trials were set up to determine the amount of sodium hypochlorite (NaOCl) (3.5% wt/vol) ranging from 0.5 to 10 mL L^{-1} that could be employed to neutralize the pathogens. The choice of NaOCl was based on its advantages as compared to other disinfection methods. For instance, NaOCl has a broad antimicrobial

spectrum, is soluble in water, relatively non-toxic to humans at recommended concentrations [30], readily available, and is typically affordable for many households [31]. Moreover, unlike UV irradiation or ozonation, disinfection by NaOCl allows residual chlorine in water, reducing the risks of microbial regrowth and recontamination [32,33].

2.7. Statistical analysis

One-way analysis of variance (ANOVA) at 95% confidence interval ($p < 0.05$) was employed to determine if there was a statistically significant difference between the mean values of the measured parameters at the various handwashing stations. Once it was found that there were statistically significant differences ($p < 0.05$), a post-hoc analysis using Tukey-Kramer test was employed to ascertain which pairwise comparisons were significantly different. The statistical analyses were performed using Microsoft Excel statistical package for Windows.

3. Results and discussion

3.1. Raw water characterization

Table 1 shows results from the characterization of raw water samples obtained from handwashing stations installed at W, Q, F, K, and N. The results revealed that the raw water employed in each of the installed stations exhibited levels of turbidity, TDS, nitrates, and pH that were within or close to levels desired of potable water (see Table 1). On the contrary, the levels of ammonia-nitrogen, total phosphorous, TSS, total coliforms, and *E. coli* exhibited by the raw water were out of the range desired of potable water. Consequently, handwashing using the raw water could pose health risks to end-users. For instance, presence of pathogens of fecal origin in the raw water samples as confirmed by the detection of *E. coli* in the raw water poses a risk of catching diseases such as dysentery, cholera, and typhoid, among others [34,35]. Moreover, the suspended solids in the raw water could make neutralization of pathogens difficult by shielding them from disinfection [36,37].

The higher values of true color of raw water employed at F and K may be mainly attributed to the presence of dissolved organic substances such as humic or fulvic acids, posing health risks to end-users [38]. For instance, humic acid could interact with the disinfectant added to the

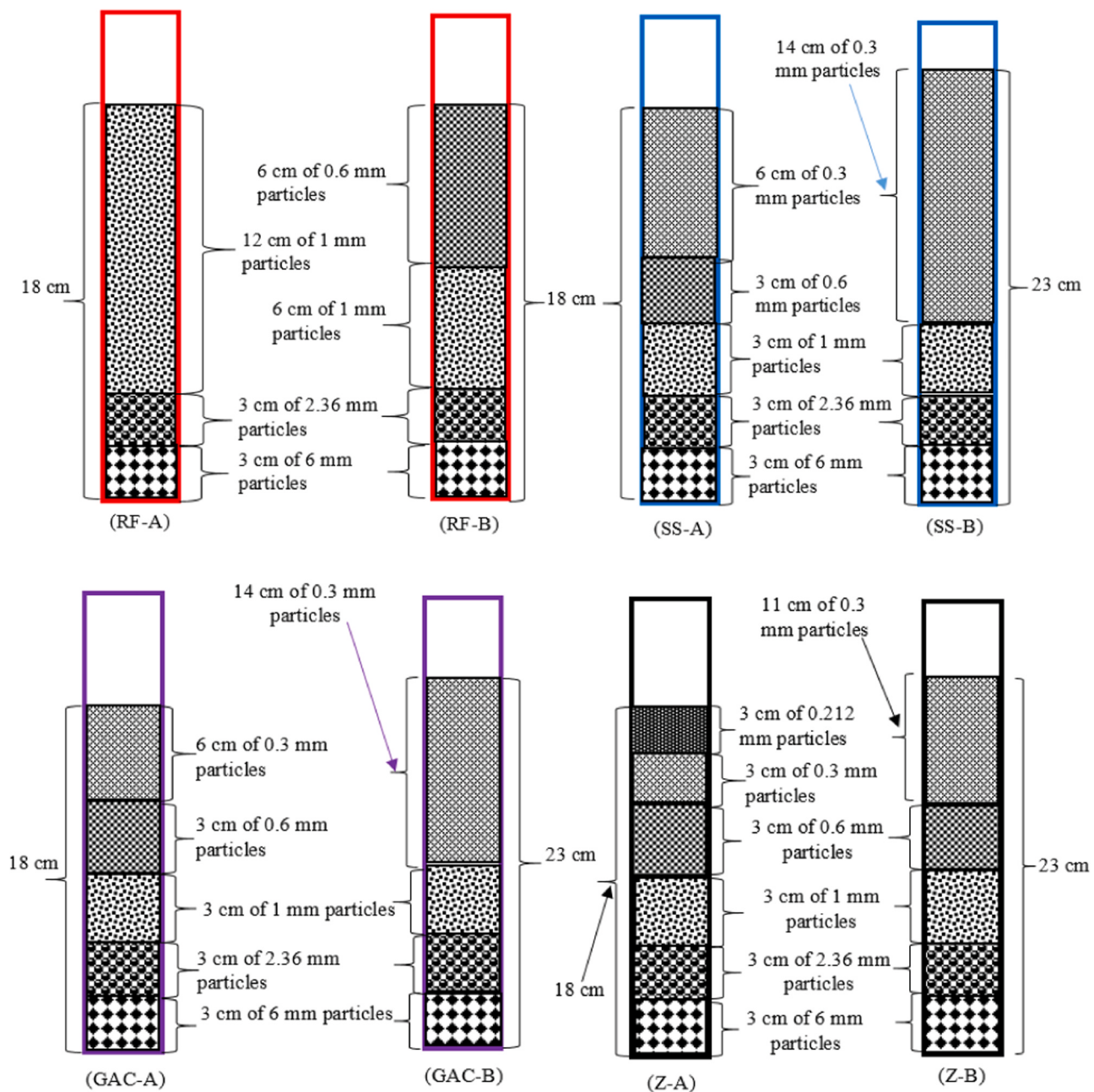


Fig. 2. Configuration of the two selected filter depth for roughing filter (RF-A and RF-B), silica sand (SS-A and SS-B), zeolite (Z-A and Z-B), and granular activated carbon (GAC-A and GAC-B). For roughing filter and silica sand, all particles were made up of sand, for zeolite all materials were made up of zeolite, for granular activated carbon, the base layer of 3 cm was made up of sand, while all other layers were of activated carbon.

raw water, forming carcinogenic disinfection byproducts (DBPs) harmful to human health [39].

From the discussion above, it can be seen that at each of the handwashing stations, the raw water did not exclusively meet the quality standards desired of potable water. However, for the strict purpose of handwashing, the raw water could be employed for the purpose since its turbidity level was below the guideline value of ≤ 20 NTU for handwashing water [40]. Moreover, provided the handwashing is done correctly with soap and with the correct technique [15], water containing *E. coli* concentration < 1000 CFU per 100 mL could still be suitable for handwashing. With this approach, *E. coli* can be removed from hands with a probability as high as $> 99.9\%$ [14]. Nonetheless, for purposes of reducing the risks of infection from hand-to-mouth contact, effort still needs to be made to use water of the highest quality possible for handwashing [14,15].

3.1.1. One-way ANOVA of raw water quality parameters

Table 2 shows results of the one-way ANOVA for the raw water quality parameters. The mean values of water quality parameters of pH, ammonia-nitrogen, total phosphorous, total coliforms, and *E. coli* were not significantly different between handwashing stations ($p > 0.05$). On the other hand, the mean values of true color, turbidity, total suspended solids, total dissolved solids, and nitrates were significantly different between stations ($p < 0.05$). However, to ascertain which pairwise comparisons were significantly different, a post-hoc analysis was conducted as described in Section 3.1.2.

3.1.2. Post-hoc analysis of the raw water quality parameters

A post-hoc analysis using Tukey-Kramer test was employed to determine which pairwise comparisons were significantly different. The Tukey-Kramer test was preferred to other methods because it is suited

Table 1
Characteristics of raw water employed for handwashing at different public facilities in Kampala.

Parameter	Selected public places in the Kampala City					Physical requirements for potable water ^a	
	W	Q	F	K	N	Treated potable water	Natural potable water
pH	5.61 ± 0.62	6.13 ± 1.58	5.78 ± 0.47	5.42 ± 0.37	5.38 ± 0.20	6.5–8.5	5.5–9.5
True color (PtCo)	36.33 ± 28.84	43.00 ± 20.87	101.00 ± 40.18	54.33 ± 26.46	42.00 ± 19.83	15	50
Turbidity (NTU)	1.50 ± 1.22	9.80 ± 9.58	17.33 ± 8.38	2.67 ± 3.27	2.17 ± 2.14	15	25
Total suspended solids (mgL ⁻¹)	5.17 ± 2.79	17.20 ± 13.37	16.00 ± 7.87	3.67 ± 3.01	4.17 ± 2.56	Not detectable	Not detectable
Total dissolved solids (mgL ⁻¹)	93.33 ± 25.88	688.00 ± 640.64	865.50 ± 499.75	100.33 ± 43.88	88.00 ± 22.94	700	1500
Nitrates (mgL ⁻¹)	2.22 ± 3.59	4.26 ± 3.28	42.03 ± 40.08	4.80 ± 3.45	1.85 ± 2.83	45	45
Ammonia-nitrogen (mgL ⁻¹)	0.11 ± 0.13	0.25 ± 0.39	0.11 ± 0.10	0.29 ± 0.65	0.12 ± 0.21	–	–
Total phosphorus (mgL ⁻¹)	5.82 ± 5.06	8.37 ± 6.75	6.91 ± 6.73	5.40 ± 5.37	5.45 ± 5.92	–	–
Total coliforms (CFU (100 mL) ⁻¹)	287.33 ± 311.54	80.80 ± 118.71	197.50 ± 226.67	1066.17 ± 2076.55	1553.33 ± 1961.79	Absent	Absent
<i>E. coli</i> (CFU(100 mL) ⁻¹)	72.33 ± 142.04	13.20 ± 29.52	24.17 ± 38.26	213.00 ± 497.56	251.00 ± 388.13	Absent	Absent

^a Implies Uganda standard for potable water according to UNBS [58].

Table 2
Results from the one-way ANOVA used to compare mean values of the raw water quality parameters between handwashing stations.

Parameter	Source of variation	SS	df	MS	F-value	p-value	F _{crit}	Significance
pH	Between groups	2.028	4	0.507	0.879	0.491	2.776	Not significant (p > 0.05)
	Within groups	13.837	24	0.577				
	Total	15.865	28					
True color (PtCo)	Between groups	16,506.644	4	4126.661	5.094	0.004	2.776	Significant (p < 0.05)
	Within groups	19,440.677	24	810.028				
	Total	35,947.310	28					
Turbidity (NTU)	Between groups	1109.235	4	277.309	8.301	0.000	2.776	Significant (p < 0.05)
	Within groups	801.800	24	33.408				
	Total	1911.035	28					
TSS (mgL ⁻¹)	Between groups	1029.166	4	257.291	5.408	0.003	2.776	Significant (p < 0.05)
	Within groups	1141.800	24	47.575				
	Total	2170.966	28					
TDS (mgL ⁻¹)	Between groups	3,345,760.799	4	836,440.200	6.908	0.000	2.776	Significant (p < 0.05)
	Within groups	2,906,024.167	24	121,084.340				
	Total	6,251,784.966	28					
Nitrates (mgL ⁻¹)	Between groups	7199.357	4	1799.839	5.244	0.004	2.776	Significant (p < 0.05)
	Within groups	8237.829	24	343.243				
	Total	15,437.186	28					
Ammonia-nitrogen (mgL ⁻¹)	Between groups	0.181	4	0.045	0.357	0.836	2.776	Not significant (p > 0.05)
	Within groups	3.047	24	0.127				
	Total	3.228	28					
Total phosphorus (mgL ⁻¹)	Between groups	44.419	4	11.105	0.310	0.868	2.776	Not significant (p > 0.05)
	Within groups	858.896	24	35.787				
	Total	903.315	28					
Total coliforms (CFU (100 mL) ⁻¹)	Between groups	9,571,760.959	4	2,392,940.240	1.380	0.270	2.776	Not significant (p > 0.05)
	Within groups	41,602,117.800	24	1,733,421.575				
	Total	41,602,117.800	28					
<i>E. coli</i> (CFU(100 mL) ⁻¹)	Between groups	280,538.344	4	70,134.586	0.800	0.537	2.776	Not significant (p > 0.05)
	Within groups	2,102,738.967	24	87,614.124				
	Total	2,383,277.310	28					

for groups with unequal sample size. The results from the test revealed that the mean values of true color, turbidity, TSS, TDS, and nitrates were not significantly different ($p > 0.05$) between handwashing stations installed at; (i) W and Q, (ii) W and K, (iii) W and N, (iv) Q and K, (v) Q and N, and (vi) K and N. On the other hand, the mean values of turbidity, TSS, TDS, and nitrates were significantly different between handwashing stations installed at; (i) F and K (ii) W and F, and (iii) F and N (see Table 3).

3.2. Wastewater characterization

Table 4 shows results from the characterization of handwashing wastewater generated at each of the handwashing stations installed at

W, Q, F, K, and N. The results revealed that the wastewater generated at each of the installed handwashing stations exhibited levels of TDS, nitrates, ammonia-nitrogen, and phosphorous that were permissible for wastewater discharge to the environment [41] (see Table 4). On the contrary, the levels of pH, BOD₅, COD, total coliform, and *E. coli* were above the permissible levels for wastewater discharge to the environment [41]. The turbidity and true color were within permissible levels at most of the installed handwashing stations (see Table 4).

The total coliform in the handwashing wastewater ranged from 1717.50 to 21,228.00 CFU per 100 mL, which was far above the permissible level of 5000 CFU per 100 mL for wastewater discharge to the environment [41]. The presence of coliform in the wastewater suggested fecal pollution of the handwashing wastewater. On the other

Table 3

Results from the post-hoc Tukey-Kramer analysis of the raw water quality parameters between handwashing stations.

Parameter	Pair-wise comparison	Abs diff.	Std error	q_{stat}	q_{crit}	Significance
True color (PtCo)	W to Q	6.667	12.186	0.547	4.166	Not significant
	W to K	18.000	11.619	1.549	4.166	Not significant
	W to N	5.667	11.619	0.488	4.166	Not significant
	Q to K	11.333	12.186	0.930	4.166	Not significant
	Q to N	1.000	12.186	0.082	4.166	Not significant
	F to K	46.667	11.619	4.016	4.166	Not significant
	K to N	12.333	11.619	1.061	4.166	Not significant
	W to F	64.667	11.619	5.566	4.166	Significant
	Q to F	58.000	12.186	4.759	4.166	Significant
	F to N	59.000	11.619	5.078	4.166	Significant
	W to Q	8.300	2.475	3.354	4.166	Not significant
	W to K	1.167	2.360	0.494	4.166	Not significant
Turbidity (NTU)	W to N	0.667	2.360	0.283	4.166	Not significant
	Q to K	7.133	2.475	2.882	4.166	Not significant
	Q to N	7.633	2.475	3.084	4.166	Not significant
	F to K	0.500	2.360	0.212	4.166	Not significant
	K to N	7.533	2.475	3.044	4.166	Not significant
	W to F	14.667	2.360	6.216	4.166	Significant
	Q to F	15.83	2.360	6.710	4.166	Significant
	F to N	15.167	2.360	6.427	4.166	Significant
	W to Q	8.30	2.47	3.35	4.166	Not significant
	W to K	1.17	2.36	0.49	4.166	Not significant
	W to N	0.67	2.36	0.28	4.166	Not significant
	Q to K	7.53	2.47	3.04	4.166	Not significant
TSS (mgL ⁻¹)	Q to N	7.13	2.47	2.88	4.166	Not significant
	F to K	7.63	2.47	3.08	4.166	Not significant
	K to N	0.50	2.36	0.21	4.166	Not significant
	W to F	15.83	2.36	6.71	4.166	Significant
	Q to F	14.67	2.36	6.22	4.166	Significant
	F to N	15.17	2.36	6.43	4.166	Significant
	W to Q	594.67	148.99	3.99	4.166	Not significant
	W to K	7.00	142.06	0.05	4.166	Not significant
	W to N	5.33	142.06	0.04	4.166	Not significant
	Q to F	177.50	148.99	1.19	4.166	Not significant
	Q to K	587.67	148.99	3.94	4.166	Not significant
	Q to N	600.00	148.99	4.03	4.166	Not significant
TDS (mgL ⁻¹)	K to N	12.33	142.06	0.09	4.166	Not significant
	W to F	772.17	142.06	5.44	4.166	Significant
	F to K	765.17	142.06	5.39	4.166	Significant
	F to N	777.50	142.06	5.47	4.166	Significant
	W to Q	2.04	7.93	0.26	4.166	Not significant
	W to K	2.58	7.56	0.34	4.166	Not significant
	W to N	0.37	7.56	0.05	4.166	Not significant
	Q to F	0.54	7.93	0.07	4.166	Not significant
	Q to K	2.41	7.93	0.30	4.166	Not significant
	Q to N	2.95	7.56	0.39	4.166	Not significant
	K to N	39.82	7.56	5.26	4.166	Not significant
	W to F	37.77	7.93	4.76	4.166	Significant
Nitrates (mgL ⁻¹)	F to K	37.23	7.56	4.92	4.166	Significant
	F to N	40.18	7.56	5.31	4.166	Significant

Note: (i) *Abs diff* implies absolute difference, (ii) *std error* implies the standard error, (iii) q_{crit} is the critical value for the studentized range distribution for q , and (iv) q_{stat} is the studentized range statistic obtained by dividing the absolute difference with the standard error.

hand, the detection of *E. coli* in the wastewater pointed to the presence of pathogens of fecal origin, which pose health risks to humans and/or animals upon contact with the wastewater [34,35]. There is thus need for treatment of the handwashing wastewater prior to its discharge to the environment. Moreover, as earlier indicated, the treated wastewater could be recycled, making it possible for more users to practice handwashing.

At all the selected public facilities, the generated handwashing wastewater was of high strength with relatively low biodegradability, since the ratios of BOD₅ to COD were < 0.5 [42]. The nutrient content of the handwashing wastewater is also typically low to sustain microbial activities [17]. Because of these reasons, biological treatment methods alone are not preferred for treatment of handwashing wastewater. Instead, alternative methods such as roughing filtration, slow sand filtration, as well as adsorption and/or filtration by zeolite, pumice, and/or granular activated carbon are better suited for handwashing wastewater treatment. For instance, since the turbidity of the handwashing wastewater was > 50 NTU, roughing filtration could help to

remove suspended solids, which would otherwise lead to frequent clogging of the slow sand filter [23,43]. Further discussion concerning treatment of the handwashing wastewater is given in Sections 3.3 and 3.4.

3.2.1. One-way ANOVA of wastewater quality parameters

Table 5 shows results from the one-way ANOVA used to compare mean values of the wastewater quality parameters between handwashing stations installed at selected public facilities. The results revealed that the mean values of pH, true color, turbidity, TDS, nitrates, ammonia-nitrogen, total phosphorous, BOD₅, COD, total coliform, and *E. coli* were not significantly different ($p > 0.05$) between handwashing stations installed at the selected public facilities. On the other hand, the mean values of total suspended solids were found to be significantly different ($p < 0.05$) between handwashing stations installed at the different public facilities. However, to further ascertain which pairwise comparisons were significantly different, a post-hoc analysis using Tukey-Kramer test was employed as described in Section 3.2.2.

Table 4

Characteristics of wastewater generated from handwashing at selected public facilities in Kampala.

Parameter	Selected public places in the Kampala City					NEMA effluent discharge standards**
	W	Q	F	K	N	
pH	5.75 ± 1.00	5.06 ± 0.61	5.35 ± 0.29	4.97 ± 0.41	5.08 ± 0.89	6.0–8.0
True color (PtCo)	586.00 ± 281.64	88.25 ± 15.71	332.60 ± 130.29	518.80 ± 424.60	370.60 ± 386.40	300
Turbidity (NTU)	310.00 ± 84.42	85.25 ± 23.67	133.20 ± 44.51	387.20 ± 387.20	288.20 ± 77.63	300
TSS (mgL ⁻¹)	258.40 ± 76.16	91.50 ± 25.65	126.80 ± 36.75	259.60 ± 161.19	273.60 ± 43.86	100
Total dissolved solids (mgL ⁻¹)	347.80 ± 139.83	870.50 ± 624.90	1169.60 ± 266.13	534.40 ± 299.40	1018.40 ± 1334.76	1200
Nitrates (mgL ⁻¹)	11.26 ± 13.10	4.78 ± 1.99	58.02 ± 42.95	82.78 ± 145.12	15.29 ± 22.66	89 (Nitrate-Nitrogen 20 mg/l)
Ammonia-nitrogen (mgL ⁻¹)	0.73 ± 0.63	0.27 ± 0.45	0.47 ± 0.73	1.01 ± 1.45	10.10 ± 20.07	10
Total phosphorus (mgL ⁻¹)	4.11 ± 4.84	5.20 ± 4.75	4.30 ± 4.85	4.11 ± 2.97	5.27 ± 5.45	10
BOD ₅ (mgL ⁻¹)	163.40 ± 100.80	180.25 ± 105.89	232.40 ± 89.38	161.20 ± 96.89	200.40 ± 87.34	50
COD (mgL ⁻¹)	531.20 ± 207.14	618.50 ± 273.83	923.20 ± 127.11	487.60 ± 318.41	721.20 ± 450.66	100
BOD ₅ /COD	0.30 ± 0.17	0.30 ± 0.16	0.26 ± 0.13	0.35 ± 0.13	0.32 ± 0.10	–
Total coliforms CFU (100 mL ⁻¹)	11,266.00 ± 9879.93	1717.50 ± 1069.12	8961.00 ± 10,414.52	13,484.00 ± 10,076.13	21,228.00 ± 21,908.96	5000
<i>E. coli</i> (CFU(100 mL ⁻¹))	4662.00 ± 4985.30	650.00 ± 570.88	3942.00 ± 3744.99	4856.60 ± 6022.80	6094.20 ± 6609.37	ns

Note: (i) NEMA implies National Environment Management Authority of Uganda, and (ii) ** implies Uganda's national effluent discharge standards, 1999 [41].

3.2.2. Post-hoc analysis of the wastewater quality parameters

A post-hoc analysis using Tukey-Kramer test was conducted to determine which pairwise comparisons were significantly different with respect to total suspended solids. The results revealed that the mean values of total suspended solids were not significantly different ($p > 0.05$) between handwashing stations, except for stations installed at Q and N. This lack of statistical significance suggests that one design of a wastewater treatment system could be suitable for removal of suspended solids from wastewater generated at any of the selected public facilities, including F, Q, N, W, and K (Table 6).

3.3. Characteristics of the filter media

Silica sand, zeolite, and GAC were employed as filtration and/or adsorption media materials for treatment of handwashing wastewater. From the manufacturer's specifications, the properties of GAC included particle size range of 3.35–1.70 mm, specific surface area of 1050 m²g⁻¹, and a particle density of 540 gm⁻³. The rest of the filter media materials (silica sand and zeolite) were characterized in this study. The results from the XRF-analysis (Table 7) revealed that SiO₂ is the major phase in silica sand and zeolite, with silica sand having a greater proportion of SiO₂ than zeolite. These findings are similar to those reported elsewhere [44,45]. However, the differences in chemical composition of the materials employed in this study and those studied elsewhere could be due to differences in their mode of formation, differences in the age of parent materials, as well as due to differences in the country of origin [46].

Fig. 3 shows the FTIR spectra of sand, zeolite, and GAC filter media materials that constituted the wastewater treatment system. The FTIR spectra of sand and zeolite followed a similar trend/shape, suggesting presence of similar surface functional groups. More specifically, the band around 2364.30 cm⁻¹ may be due to –OH stretching and vibration, suggesting presence of moisture on the surfaces of sand and zeolite [48]. The presence of moisture on surfaces of the two filter media materials was also confirmed by results from the XRF analysis (see Table 7). The band around 996.05 cm⁻¹ may be attributed to the Si–O–Si and Si–O–Al linkage in zeolite [49], while the band around 671.11 cm⁻¹ may be attributed to presence of Si–O in the sand [50]. In the case of GAC, the band around 3381.57 cm⁻¹ may be attributed to –OH stretching, suggesting presence of adsorbed water, alcohols, phenols and/or carboxyl groups on the surface of the activated carbon [51]. The band around 2981.41 cm⁻¹ may be attributed to C–H stretching of aliphatic –CH and –CH₃ [52]. Lastly, the bands around 1650.00 and 682.68 cm⁻¹ may be attributed to C=C stretching and C–H out of plane bending aromatic

rings, respectively [53].

Fig. 4 shows the SEM images of sand, zeolite, and GAC filter media materials that constituted the wastewater treatment system. The SEM images show that GAC exhibited more pores, followed by zeolite, and then sand. The images also show that zeolite had a rougher surface as compared to GAC and sand. The high porosity of GAC and the rougher surface of zeolite are the most important factors that make them suitable adsorbents [54]. On the other hand, due to the low porosity and smooth surface of sand, less removal efficiency would be achieved through adsorption. Instead, much of the removal efficiency by sand would be achieved via physical filtration and/or biological processes [21].

3.4. Performance of the constructed wastewater treatment systems

3.4.1. Performance of the individual filtration units

The individual filtration units included the roughing filter, slow sand filter, as well as the zeolite- and the GAC-based filters. The results from the performance evaluation of the constructed filters (see Fig. 2) are presented in Table 8. The results revealed that, for given physical parameters of turbidity, true color, apparent color, and TSS, the removal efficiency decreased in the order GAC-B > GAC-A > Z-A > Z-B > SS-B > SS-A > RF-B > RF-A. Elsewhere [55], sand was found to be more effective at removing turbidity than GAC. The low turbidity removal by the roughing and silica sand filters may be attributed to the relatively large particle sizes of the filter media materials (see Fig. 2), which could not effectively remove the bulk of the finer solid material present in the handwashing wastewater. According to Schneider et al. [56], silica sand with particle sizes between 0.1 and 0.35 mm ensures excellent turbidity removal from water, with the removal efficiency increasing with a decrease in particle size.

The removal of turbidity was highest with GAC (73.63–77.32%) and zeolite (49.67–55.69%) as compared to silica sand (23.83–42.53%) and the roughing filter (8.90–13.11%). The superior performance by GAC and zeolite may be attributed to the pollutant removal mechanisms, combining (i) adsorption [26], (ii) physical filtration [57], and (iii) biological degradation [58]. However, in spite of this superior performance, none of the filtrate obtained from the individual filtration units met the permissible level desired of handwashing water. For instance, the turbidity of the filtrate at each of the individual filtration units was above 20 NTU; the permissible level desired of handwashing water [40]. Similarly, the physical parameters of the filtrate were above those desired of portable water [59]. The filtrate was also not suitable for potable water reuse as stipulated by the US EPA 2012 Guidelines for

Table 5

Results from the one-way ANOVA used to compare mean values of the wastewater quality parameters between handwashing stations installed at selected public facilities.

Parameter	Source of variation	SS	df	MS	F-value	p-value	F _{crit}	Significance
pH	Between groups	1.994	4	0.498478	1.020	0.422	2.895	Not significant (p > 0.05)
	Within groups	9.285	9	0.488685				
	Total	11.279	23					
True color (PtCo)	Between groups	657,550.506	4	164,387.627	1.833	0.164	2.895	Not significant (p > 0.05)
	Within groups	1,704,298.374	19	89,699.914				
	Total	2,361,848.880	23					
Turbidity (NTU)	Between groups	296,015.350	4	74,003.838	2.119	0.118	2.895	Not significant (p > 0.05)
	Within groups	663,415.150	19	34,916.587				
	Total	959,430.500	23					
TSS (mgL ⁻¹)	Between groups	134,738.433	4	33,684.608	4.500	0.010	2.895	Significant (p < 0.05)
	Within groups	142,209.400	19	7484.705				
	Total	276,947.833	23					
TDS (mgL ⁻¹)	Between groups	2,310,924.558	4	577,730.890	1.217	0.336	2.895	Not significant (p < 0.05)
	Within groups	9,017,293.400	19	474,594.389				
	Total	11,328,217.958	23					
Nitrates (mgL ⁻¹)	Between groups	22,468.011	4	5617.003	1.131	0.372	2.895	Not significant (p < 0.05)
	Within groups	94,369.154	19	4966.798				
	Total	116,837.165	23					
Ammonia-nitrogen (mgL ⁻¹)	Between groups	356.083	4	89.021	1.041	0.412	2.895	Not significant (p < 0.05)
	Within groups	1624.399	19	85.495				
	Total	1980.481	23					
Total phosphorus (mgL ⁻¹)	Between groups	6.544	4	1.636	0.076	0.989	2.895	Not significant (p < 0.05)
	Within groups	409.357	19	21.545				
	Total	415.901	23					
BOD ₅ (mgL ⁻¹)	Between groups	17,482.183	4	4370.546	0.476	0.753	2.895	Not significant (p < 0.05)
	Within groups	174,301.150	19	9173.745				
	Total	191,783.333	23					
COD (mgL ⁻¹)	Between groups	603,439.233	4	150,859.808	1.707	0.190	2.895	Not significant (p < 0.05)
	Within groups	1,679,120.600	19	88,374.768				
	Total	2,282,559.833	23					
Total coliforms (CFU (100 mL) ⁻¹)	Between groups	9.06856425.625	4	226,714,106.406	1.366	0.283	2.895	Not significant (p < 0.05)
	Within groups	3,153,853,215.000	19	165,992,274.474				
	Total	4,060,709,640.625	23					
<i>E. coli</i> (CFU(100 mL) ⁻¹)	Between groups	71,898,064.500	4	17,974,516.125	0.717	0.591	2.895	Not significant (p < 0.05)
	Within groups	476,321,514.000	19	25,069,553.368				
	Total	548,219,578.500	23					

Table 6

Results from the post-hoc Tukey-Kramer analysis of the TSS of wastewater between handwashing stations installed at different public facilities.

Pair-wise comparison	Abs diff.	Std error	q_{stat}	q_{crit}	Significance
W to Q	157.000	41.037	3.826	4.253	Not significant
W to K	4.267	38.690	0.110	4.253	Not significant
W to N	18.267	38.690	0.472	4.253	Not significant
Q to K	161.267	41.037	3.930	4.253	Not significant
F to K	132.800	38.690	3.432	4.253	Not significant
K to N	14.000	38.690	0.362	4.253	Not significant
W to F	128.533	38.690	3.322	4.253	Not significant
Q to F	28.467	41.037	0.694	4.253	Not significant
F to N	146.800	38.690	3.794	4.253	Not significant
Q to N	175.267	41.037	4.271	4.253	Significant

Note: (i) *Abs diff* implies absolute difference, (ii) *std error* implies the standard error, (iii) q_{crit} is the critical value for the studentized range distribution for q , and (iv) q_{stat} is the studentized range statistic obtained by dividing the absolute difference with the standard error.

Water Reuse [60]. Moreover, at some of the filtration units, the physical parameters of the filtrate were above the standards for effluent wastewater discharge [41]. To achieve improvements in the removal of pollutants from wastewater, the individual filtration units were serially configured into a single filtration column. The performance of the resultant filtration column is discussed in Section 3.4.2.

3.4.2. Performance of the combined filtration units

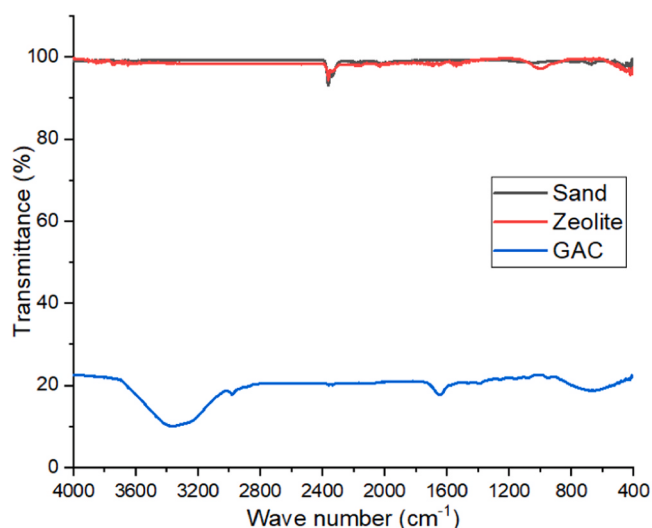
The individual filtration units studied under Section 3.4.1 were serially configured into a single filtration column, with the GAC deployed at the bottom, followed by silica sand (SS), and lastly the roughing filter (RF) at the top of the column. The resultant filtration system was subsequently investigated to arrive at the configuration which results in the highest removal of physical parameters from the handwashing wastewater. As can be seen from Table 9, the pH of the filtrate from each of the serially configured filter columns was within levels permissible for portable and drinking water [23,59]. The turbidity of the filtrate was also within levels permissible for handwashing water (UNICEF, 2020). However, the apparent color and total suspended solids of the filtrate were above the permissible levels (see Table 9).

Table 7

Characteristics of the different filter media materials.

Filter medium	Composition of the different filter media materials									Country of origin	Ref
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	LOI		
Silica sand	95.6083	0.5262	3.1914	0.5429	0	0.0031	0.1280	0	0.52	Uganda	This study
Zeolite	40.4211	20.6307	17.9913	11.6746	2.3626	0.2274	2.5702	4.1222	12.42	Uganda	This study
Silica sand	96.62	1.54	–	0.57	0.57	–	–	–	–	India	[44]
Silica sand	88.80–97.43	1.25–5.88	0.63–2.33	–	0.08–0.20	–	0.06–2.68	–	0.12–0.37	Tunisia	[45]
Zeolite	67.03	12.07	0.89	3.66	0.74	0.01	0.71	0.67	9.74	Australia	[46]
Zeolite	73.6	13.5	1.60	3.65	0.704	–	4.24	0.838	–	Greece	[47]

Note: LOI is loss on ignition.

**Fig. 3.** FTIR spectra of sand (a), zeolite (b), and GAC (c).

Color removal from the wastewater was achieved by each filter media material partly due to the acidic functional groups present on their surfaces (see Section 3). The functional groups favor the removal of color [61,62], with a combination of physical filtration and adsorption processes. Though not quantified in this study, foam was not visible in the filtrate upon visual inspection, suggesting that the surfactants were effectively removed from the handwashing wastewater. These could have been significantly removed by GAC as compared to zeolite and silica sand [55]. These results are in agreement with those indicated in Section 3.4.1.

Overall, the serial configuration RF-A, SS-B, Z-B, and GAC-B with a total retention time of 32.2 min exhibited the best performance,

removing turbidity, true color, apparent color, and TSS with efficiencies of 98.50%, 98.06%, 99.67%, and 96.93%, respectively. This was followed by RF-B, SS-B, Z-B, and GAC-B with a total retention time of 47.0 min, RF-B, SS-A, Z-A, and GAC-A with a retention time of 27.3 min, and lastly RF-A, SS-A, Z-A, and GAC-A with a total retention time of 24.5 min. These results showed that the combined filtration unit offers improved removal of physical parameters from the handwashing wastewater as compared to the individual filtration units. This progressive improvement may be attributed to the combined removal effect of the different filter media employed in the configured filtration system. These results are corroborated with those reported by Aly et al. [63], where the color and turbidity of olive mill wastewater were found to decrease at each filter stage in the combined wastewater treatment system, consisting of gravel, fine sand, zeolite, and activated carbon. It is however worth noting that the filtrate from the best performing filter configuration (RF-A, SS-B, Z-B, and GAC-B) still exhibited total coliform and *E. coli* of 1395 and 1180 CFU per 100 mL, respectively. This was expected since the nutrient content of the handwashing wastewater is typically low to sustain microbial activities [17]. Consequently, the predatory bacteria in the resultant biofilm could not effectively feed on the pathogens passing through the filter [21]. However, with the filtrate having a turbidity ≤ 5 NTU, the pathogenic microorganisms present in the filtrate could be effectively destructed during the disinfection process [64]. This is because at such low turbidity levels, the particulate matter present in the filtrate cannot effectively shield the pathogenic microorganisms from the disinfectant during the disinfection process. The performance evaluation of the disinfection process for deactivation of the pathogenic microorganisms still present in the filtrate is given under Section 3.4.3.

3.4.3. Deactivation of coliforms and *E. coli*

As noted in Section 3.4.2, the best performing configuration of the treatment media did not totally eliminate coliforms and *E. coli*. The residual amounts of the forenamed parameters in the filtrate were above

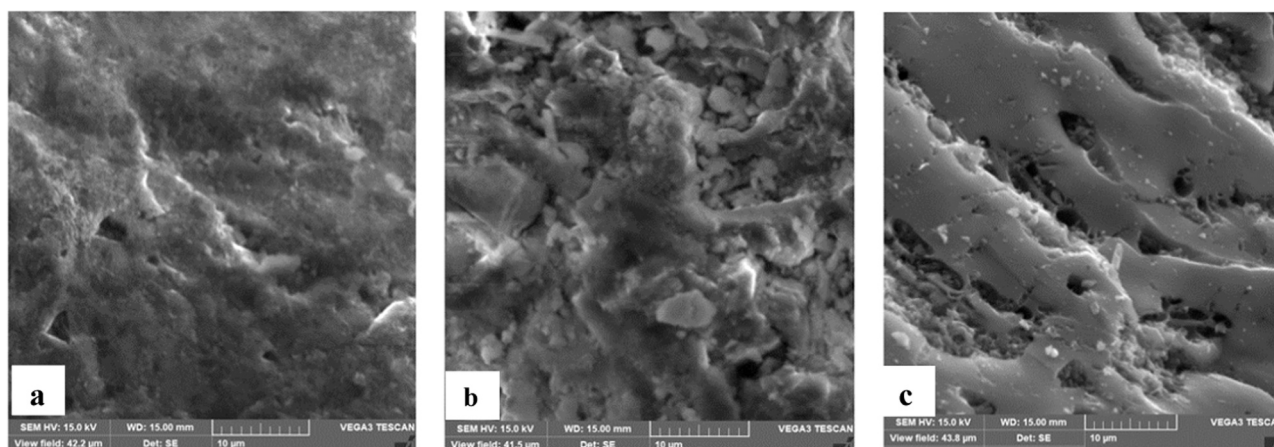
**Fig. 4.** SEM images for sand (a), zeolite (b), and GAC (c) filter media materials.

Table 8
Performance of each constructed filter medium for removal of selected physical parameters from handwashing wastewater.

Parameter	Wastewater	Individual filter media filtrate						Physical requirements for potable water ^a				NEMA standards for effluent wastewater discharge ^b	US EPA standards for potable water reuse ^c
		RF-A	RF-B	SS-A	SS-B	Z-A	Z-B	GAC-A	GAC-B	Treated potable water	Natural potable water		
pH	5.55 ± 0.21	5.50 ± 0.12	5.53 ± 0.16	5.61 ± 0.26	5.42 ± 0.09	5.86 ± 0.12	5.55 ± 0.18	7.88 ± 0.13	8.03 ± 0.45	6.5–8.5	5.5–9.5	6.0–8.0	6.5–8.5
Turbidity (NTU)	348.33 ± 78.39	317.33 ± 85.35	302.67 ± 81.92	265.33 ± 71.22	203.67 ± 36.06	154.33 ± 23.89	175.33 ± 23.21	95.33 ± 15.69	79.00 ± 14.24	15	25	≤ 300	≤ 2
True color (PtCo)	637.33 ± 193.88	580.00 ± 188.59	542.00 ± 199.15	453.00 ± 180.39	434.33 ± 180.30	296.33 ± 117.95	315.67 ± 118.55	162.00 ± 50.99	143.33 ± 50.31	15	50	≤ 300	–
Apparent color	2614.67 ± 923.61	2177.00 ± 703.85	2034.00 ± 690.03	1656.33 ± 371.69	1386.00 ± 310.15	863.00 ± 229.05	987.33 ± 196.78	456.3 ± 100.02	398.33 ± 66.62	–	–	–	–
TSS (mgL ⁻¹)	471.67 ± 75.12	426.00 ± 73.54	404.00 ± 50.64	304.67 ± 24.39	275.67 ± 25.30	137.00 ± 20.61	158.67 ± 18.35	107.33 ± 23.70	98.67 ± 19.87	Not detectable	Not detectable	≤ 100	≤ 5
Retention time (min)	–	4.00 ± 1.41	7.08 ± 1.63	11.00 ± 1.41	14.67 ± 1.70	24.00 ± 3.27	19.67 ± 2.62	11.33 ± 1.25	16.33 ± 1.25	–	–	–	–

^a Implies Uganda standard for potable water according to UNBS [59], NEMA Implies National Environment Management Authority of Uganda.

^b Implies Uganda's national effluent discharge standards [41].

^c Implies US EPA standard for potable water reuse [60].

Table 9
Physical characteristics of the wastewater and the filtrate from the different serially configured filtration units at different total retention times.

Serial configuration*/ standards	RT (min)	Physical parameters of wastewater				Physical parameters of the filtrate from the different serially configured filtration units						
		pH	Turbidity (NTU)	True color (PtCo)	Apparent color (PtCo)	TSS (mgL ⁻¹)	pH	Turbidity (NTU)	True color (PtCo)	Apparent color (PtCo)	TSS (mgL ⁻¹)	
RF-A, SS-A, Z-A, GAC-A	24.5	6.05 ± 0.33	336.33 ± 54.82	542.33 ± 80.75	2049 ± 109.95	307.67 ± 58.00	7.21 ± 0.59	19.00 ± 2.16	27.00 ± 9.09	157.00 ± 14.16	17.33 ± 3.95	
RF-A, SS-B, Z-B, GAC-B	32.2	5.93 ± 0.27	309.33 ± 24.57	533.67 ± 64.37	2025.33 ± 101.92	282.67 ± 32.10	8.19 ± 0.17	4.67 ± 4.10	10.33 ± 7.59	6.33 ± 4.64	8.67 ± 2.60	
RF-B, SS-A, Z-A, GAC-A	27.3	5.80 ± 0.19	357.67 ± 59.89	500.67 ± 55.25	2074.67 ± 216.23	288.00 ± 31.84	7.59 ± 0.78	14.00 ± 2.45	38.00 ± 26.19	17.33 ± 2.87	19.00 ± 2.94	
RF-B, SS-B, Z-B, GAC-B	47.0	5.82 ± 0.14	333.00 ± 51.58	548.67 ± 90.68	2070.33 ± 125.93	296.33 ± 4.44	7.72 ± 0.79	10.33 ± 3.40	13.67 ± 5.74	80.00 ± 14.99	15.67 ± 3.30	
Potable water ^a	–	–	–	–	–	–	6.5–8.5	15	15	–	Not detectable	
Natural potable water ^a	–	–	–	–	–	–	5.5–9.5	25	50	–	Not detectable	
Standards for drinking water ^b	–	–	–	–	–	–	6.5 – 8.5	≤ 5	≤ 15	Nil	Nil	

Note: (i) *For purposes of visualizing the selected individual filtration units, we refer the reader to Fig. 2, under Section 2.5, (ii) RT implies the total retention time the wastewater was allowed to run through the combined filtration system, (iii) ^aImplies Uganda standard for potable water according to UNBS [59], and (iv) ^bImplies Standards for drinking water according to WHO [23].

the permissible levels prescribed for handwashing water by Verbyla et al. [14]. A number of experimental trials were set up to determine the appropriate dosage of NaOCl (3.5% wt/vol) capable of neutralizing the pathogens still present in the filtrate (see Section 2.5). The results from the experimental trials revealed that disinfection at 0.5 mL NaOCl (3.5% wt/vol) per liter of filtrate completely deactivated the pathogens. Compared to the dosage of 4 mL⁻¹ of Water Guard employed elsewhere [65,66], the dosage obtained in this study equally provides an economical and practical path for disinfection of the filtrate. This is because the typically lower concentration of NaOCl in Water Guard (1% wt/vol) [32], can be compensated for with the need for a lower volume of NaOCl employed in this study.

4. Conclusion

This study aimed at development and appraisal of a handwash-wastewater treatment system for water recycling as a resilient response to COVID-19. Samples of handwashing raw water were obtained from selected public facilities and subsequently characterized for various parameters including pH, true color, turbidity, total suspended solids, total dissolved solids, nitrates, ammonia-nitrogen, total phosphorous, total coliforms, and *E. coli*. Similarly, the resultant handwashing wastewater was characterized to inform the design of an appropriate handwashing wastewater treatment system for potential recycling of the treated water. The study revealed that the raw water employed for handwashing at the selected public facilities did not exclusively meet the permissible levels for potable water. However, based on the minimum WHO quality requirements, the raw water was considered suitable for handwashing purpose. The *E. coli* present in the raw water could then be neutralized by disinfection and/or by correctly using soap during handwashing. This could subsequently reduce the risks of infection from hand-to-mouth contacts. The results further revealed that the handwashing wastewater generated at each of the selected public facilities did not meet the permissible levels for wastewater discharge to the environment, suggesting the need for wastewater treatment prior to its discharge to the environment. The high turbidity (> 50 NTU) exhibited by the handwashing wastewater pointed to the need for a roughing filter prior to slow sand filtration. This could help remove a significant amount of suspended solids from the wastewater, which would otherwise lead to frequent clogging of the slow sand filter. The ratio of BOD₅ to COD revealed that the wastewater had a low biodegradability, thus not amenable to biological treatment processes. The roughing filter, silica sand filter, as well as the zeolite and GAC-based filters were configured into a single treatment system for handwashing wastewater treatment. The filtrate after running through the configured wastewater treatment system exhibited a turbidity of 5 NTU, true color of 10 Pt-Co, apparent color of 6 Pt-Co, and TSS of 9 mgL⁻¹, translating to removal efficiencies of up to 98.5%, 98.1%, 99.7%, and 96.9%, respectively. Coliforms and *E. coli* in the filtrate were neutralized upon disinfection with 0.5 mL NaOCl (3.5% wt/vol) per liter of filtrate, making the filtrate suitable for handwashing purpose. This approach provides a resilient response to COVID-19, where communities faced with water scarcity can still have opportunity to practice handwashing, abating high risks of infection which could otherwise arise.

CRedit authorship contribution statement

Peter Wilberforce Olupot: Conceptualization, Methodology, Validation, Writing – original draft, Supervision, as well as Fund acquisition. **Emmanuel Menya:** Conceptualization, Data curation, Validation, Formal analysis, Writing – review & editing. **Joseph Jjagwe:** Conceptualization, Investigation, Formal analysis, Writing – review & editing, Project administration. **Joel Wakatuntu:** Investigation, Methodology. **Tonny Kavuma:** Investigation, Resources. **Andrew Wabwire:** Investigation, Resources. **Steven Kavuma:** Investigation, Resources. **Samuel Okodi Mcmondo:** Conceptualization, Supervision. **Betty Nabuuma:**

Supervision, Review & editing. **Herbert Mpagi Kalibbala:** Conceptualization, Supervision, Resources.

Funding information

This research was made possible with support from the Government of the Republic of Uganda through Makerere University Research and Innovations Fund Grant No. RIF-000693-06, as well as with support from the Volkswagen Foundation, Grant 96659-1.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Technical support from Dr. Robinah Kulabako and Ms. Rita Nakazibwe at the Department of Civil and Environmental Engineering, Makerere University, is gratefully acknowledged.

Conflicts of interest

The authors declare that they have no conflict of interest.

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