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Assessment of low-cost, non-electrically powered chlorination devices for gravity-driven membrane water kiosks in eastern Uganda

Lukas Dössegger, Alan Tournefier, Laura Germann, Nicola Gärtner, Timon Huonder, Cosmas Etenu, Kennedy Wanyama, Henry Ouma, and Regula Meierhofer

Abstract: *Recontamination during transport and storage is a common challenge of water supply in low-income settings, especially if water is collected manually. Chlorination is a strategy to reduce recontamination. We assessed seven low-cost, non-electrically powered chlorination devices in gravity-driven membrane filtration (GDM) kiosks in eastern Uganda: one floater, two in-line dosers, three end-line dosers (tap-attached), and one manual dispenser. The evaluation criteria were dosing consistency, user-friendliness, ease of maintenance, local supply chain, and cost. Achieving an adequate chlorine dosage (~2 mg/L at the tap and ≥ 0.2 mg/L after 24 h of storage in a container) was challenging. The T-chlorinator was the most promising option for GDM kiosks: it achieved correct dosage (CD, 1.5–2.5 mg/L) with a probability of 90 per cent, was easy to use and maintain, economical, and can be made from locally available materials. The other in-line option, the chlorine-dosing bucket (40 per cent CD) still needs design improvements. The end-line options AkvoTur (67 per cent CD) and AquatabsFlo® (57 per cent CD) are easy to install and operate at the tap, but can be easily damaged in the GDM set-up. The Venturi doser (52 per cent CD) did not perform satisfactorily with flow rates > 6 L/min. The chlorine dispenser (52 per cent CD) was robust and user-friendly, but can only be recommended if users comply with chlorinating the water themselves. Establishing a sustainable supply chain for chlorine products was challenging. Where solid chlorine tablets were locally rarely available, the costs of liquid chlorine options were high (27–162 per cent of the water price).*

Keywords: point-of-collection chlorination, water treatment, recontamination, GDM water kiosk, low-income country

Lukas Dössegger (Lukas.doessegger@eawag.ch), Project Officer, Swiss Federal Institute of Aquatic Science and Technology (Eawag); Alan Tournefier, MSc student, Eawag; Laura Germann, MSc student, Eawag; Nicola Gärtner, MSc student, Eawag; Timon Huonder, BSc student, Eawag; Cosmas Etenu, Field Technician, Africa Water Solutions, Uganda; Kennedy Wanyama, Project Manager, Africa Water Solutions, Uganda; Henry Ouma (houma@africawatersolutions.org), Project Leader, Africa Water Solutions, Uganda; Regula Meierhofer, Group Leader, Swiss Federal Institute of Aquatic Science and Technology (Eawag)

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SUSTAINABLE DEVELOPMENT GOAL (SDG) 6 calls for universal and equitable access to safe and affordable drinking water for all by 2030. Water kiosks contribute to SDG 6 by providing safe water at the community level in rural areas. Water is considered as safe if it meets the microbial guideline of the World Health Organization (WHO), which requires that *E. coli* must not be detected in any 100 ml sample (WHO, 2017). Even though water might be safe at a communal water source, microbial water quality often deteriorates during transport and storage after collection (Wright et al., 2004; Harris et al., 2013; Opryszko et al., 2013; Meierhofer et al., 2019). Typically, 20 L jerry cans are used to transport and store drinking water in rural areas. Biofilms that grow inside these plastic containers and poor water, sanitation and hygiene (WASH) conditions can lead to recontamination (Jagals et al., 2003; Mellor et al., 2013; Opryszko et al., 2013). As a result, the water no longer meets the WHO microbial guideline at the point of consumption.

Chlorination is a water treatment strategy that provides residual disinfection, reducing recontamination risks during transport and storage. WHO recommends a concentration of 0.2–0.5 mg/L free residual chlorine (FRC) at the point of consumption (WHO, 2017). Consistent provision and consumption of treated water is important to maintain good health (Hunter, 2009; Brown and Clasen, 2012; Enger et al., 2013). However, users' compliance with chlorinating water at the household level often is inadequate and establishing the necessary level of compliance has been found to be difficult (McLaughlin et al., 2009; Levy et al., 2014). The installation of a chlorinator at the point of collection would circumvent the need to establish user compliance and can increase the proportion of chlorinated water available for consumption. Therefore, the objective of our study was to assess low-cost, non-electrically powered chlorinators at the point of collection.

Methods

Gravity-driven membrane filtration water kiosks

Together with local partners, five gravity-driven membrane (GDM) kiosks were constructed in low-income areas in eastern Uganda, with ultrafiltration membranes driven by gravity filter surface water pumped up with solar pumps from Lake Victoria (total organic carbon: 8 mg/L, pH: 6, turbidity: usually 10–25 NTU, peaks up to 150 NTU (Peter-Varbanets et al., 2017)). After filtration, the water at the tap meets the WHO microbial guideline value, but recontamination after transport and storage at the household level has been observed (Meierhofer et al., 2017). A scheme of the GDM kiosk is presented in Figure 1.

Assessed chlorinators

Chlorinators can be electrically powered or non-electrically powered. Only non-electrically powered chlorinators were assessed in our study (Table 1): a manual chlorinator (chlorine dispenser), a diffusion chlorinator (floater), and water-powered chlorinators, that is, in-line (T-chlorinator, chlorine-dosing bucket (CDB)) and end-line (AquatabsFlo®, AkvoTur, Venturi).

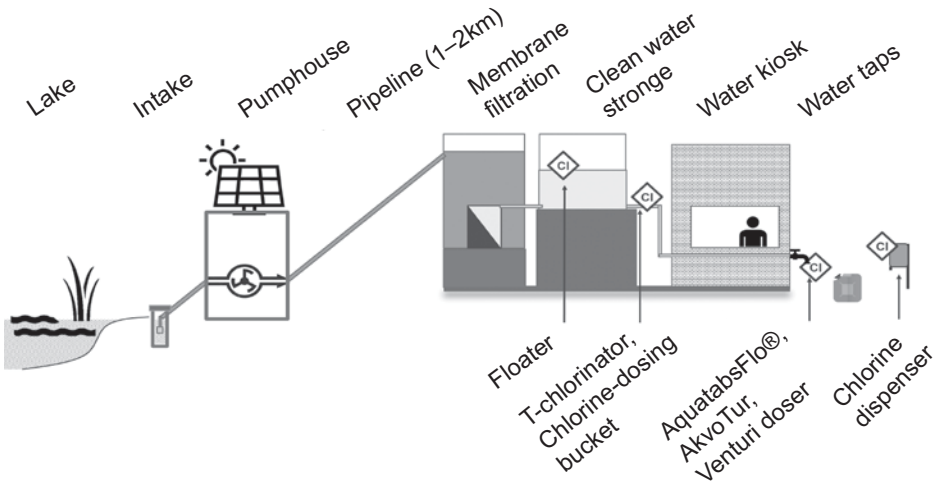
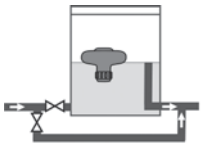


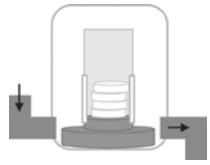
Figure 1 Scheme of GDM kiosk showing the different installation locations of assessed chlorinators

Table 1 Description of chlorinators assessed

Picture	*Device* (installation)	*Description*
	**Floater** *(Clean water storage)* Multiple manufacturers (e.g. Intex Recreation Corp, California)	The floater floats in the clean water storage tank. Slowly dissolving 90% trichloroisocyanuric acid (TCCA) tablets (Ø = 3 inches) are placed into the device and dissolve in the water. Opening or closing the slits at the bottom of the floater, as well as changing the number of tablets and the number of floaters, allow for adjusting the dosage.
	**Chlorine-dosing bucket (CDB)** *(In-line)* Design by Eawag 	The CDB is an air-tight closed bucket (30 L) with a bypass pipe that was installed in-line between the clean water tank and the kiosk's tap. A floater (see above), containing TCCA tablets (Ø = 3″), is placed inside the bucket. Valves at the inflow of the bucket and the bypass regulate the proportion of water passing through the CDB versus the bypass pipe and thereby regulate dosing. The higher the proportion of water passing through the bucket, the higher the chlorine concentration. To improve mixing behaviour, the inlet to the bucket is at the bottom and the outlet at the water surface. This is attained by an elbow with a ~10 cm pipe facing upwards attached to the outlet.
	**T-chlorinator** *(In-line)* Adapted from Orner et al. (2017)	The T-chlorinator consists of a cylinder with small holes that is placed into a T-fitting. It was installed in-line between the clean water tank and the kiosk's tap. The cylinder contains TCCA tablets (Ø = 1″), which are eroded by the flow of water. To adjust the dosage the number of tablets can be altered. Alternatively, different cylinders with different amounts and sizes of holes can be manufactured and can easily be exchanged.

(Continued)

Table 1 Continued

Picture	*Device* (installation)	*Description*
 Credit: SWAP Kenya	**Venturi doser** *(Tap)* Mountain Safety Research (MSR, 2017)	The Venturi doser uses the Venturi effect for chlorine dosage. Water passes from a pipe with a large diameter to a pipe with a smaller diameter. This leads to an increase in flow velocity, while the static fluid pressure decreases. The pressure difference at the constriction causes liquid chlorine to be 'sucked in'. The Venturi doser needs to be operated end-of-pipe and, therefore, was installed right before the tap. A 1.2% NaOCl solution was used to refill the device. A needle valve that restricts the flow regulates the dosing.
	**AquatabsFlo®** *(Tap)* (Manufactured by Medentech in Ireland)	Water flowing through the AquatabsFlo® dissolves sodium dichloroisocyanurate (NaDCC) tablets placed inside the cartridge. The device was installed after the tap with a bayonet catch for easy removal. Tablets are not sold separately; thus, the entire device is replaced if the chlorine is used up. The concentration can be adjusted with a screw, restricting the outflow, and thereby increasing the contact time with the chlorine tablets.
	**AkvoTur** *(Tap)* Design by Eawag 	Similar to the AquatabsFlo®, the device is installed after the tap. At the bottom of a container (ca. 1 L, not airtight), a PVC plate is fixed, on which a PVC pipe can be placed. The pipe has two 2-mm slits. Water enters through one slit, erodes the TCCA tablets (Ø = 1″) inside and leaves through the opposite slit. To adjust the dosage, the PVC pipe can be turned. The more the slits face in the direction of the flow, the higher the concentration.
	**Chlorine dispenser** *(Jerry can)* Evidence Action (Ahuja, 2017)	The chlorine dispenser is a container with a ball valve. It was the only 'non-passive' option evaluated and was located next to the water kiosk building. The case protects the chlorine from heat and, therefore, slows down decay. Customers place their 20 L jerry can filled with water below the dispenser and turn the ball valve to add chlorine to the jerry can. One turn releases 3 ml of a 1.2% NaOCl.

A continuous and constant flow rate is optimal for water-powered and diffusion chlorinators (Skinner, 2001). GDM systems are therefore challenging to these kinds of chlorinators because the flow rate is variable (3–24 L/min) and the pressure is low (2–30 kPa). The flow rate is determined by the water level in the storage tank and the height of the tank, and the pressure by the height difference between the level in the storage tank and the tap.

Adequate dosing

Adequate dosing requires balancing several criteria. Branz (2017) advises to 1) meet the chlorine demand of the water; 2) maintain sufficient free residual chlorine (FRC) concentrations during transport and storage; and 3) avoid exceeding international maximum guideline values and user taste and odour objections. In the study area, the average chlorine demand was 1.8 mg/L over 24 h of storage in an uncleaned jerry can (n = 46, standard deviation (SD) = 0.3 mg/L). Wilhelm et al. (2018) and international guidelines (WHO, 2017; CDC, 2020) recommend ≥ 0.2 mg/L FRC after 24 h of transport and storage. WHO (2017) recommends a maximum of 5 mg/L FRC. Taste acceptability limits vary. In Bangladesh, the acceptability limit was found to be 'well below 2 mg/L' (Crider et al., 2018), while in Zambia, water with 2 mg/L FRC was rated 'too strong and bitter', and in Ethiopia, 2 mg/L was 'noticeable' (Lantagne, 2008). In contrast, water tastings with households (n = 197, n = sample number) in the study area revealed a high acceptance of water chlorinated with 2 mg/L FRC.

Balancing the three criteria, we targeted a FRC concentration of 2 mg/L at the tap. This is slightly higher than Wilhelm et al. (2018) recommend (1.88 mg/L) for improved or low turbidity sources for 24 h protection. The higher target concentration is due to the relatively high chlorine demand measured in the study area. Reasons for the high chlorine demand include biofilms attached to the storage container's walls and deposits (Jagals et al., 2003; Mellor et al., 2013; Opryszko et al., 2013), as well as the absence of a lid on most storage containers (Lantagne, 2008; Ali et al., 2015). Additionally, the high content of organic compounds (total organic carbon = 8 mg/L) in the lake water could increase chlorine demand, similarly as observed in piped networks (Lu et al., 1999; Yee et al., 2006).

Different chlorine products

Solid and liquid chlorine products were used. The solid tablet form of chlorine is easier to handle and store as opposed to liquid chlorine, which has a shorter shelf life (Clasen and Edmondson, 2006). Solid chlorine was used in the form of slowly dissolving 90 per cent TCCA tablets and NaDCC tablets. Three-inch TCCA tablets (Henkel Polymer Ltd, US$0.01/m^3 for 2 mg/L; exchange rate: US$1 = UGX 3,800) were available in Kampala, Uganda, at the time of the study. One-inch TCCA tablets were imported from Switzerland for the study. After the study, our local partner was able to purchase them in Nairobi ($0.02/m^3 for 2 mg/L). NaDCC (Medentech, $0.22/m^3 for 2 mg/L) tablets are available in Uganda (direct communication by Medentech). Liquid chlorine was purchased at the local market as 1.2 per cent sodium hypochlorite solution (NaOCl, $0.82–0.96/m^3 for 2 mg/L) or self-produced as NaOCl solution (0.5–0.6 per cent), using a Mini-WATA™ electrochlorinator (Antenna Foundation, $280). For liquid chlorine, the WATA system is economically attractive (~$0.15–0.59/m^3 for 2 mg/L, including salt cost and device cost; lifespan of device: 1–5 years; water production: 600–1,200 m^3/year) and circumvents the need for a chlorine supply chain. Nevertheless, the local kiosk operators expressed difficulties in handling and operating the device.

Evaluation criteria

For each criterion, we developed a rating system and 'good', 'moderate', and 'poor' were the possible ratings.

Dosing consistency. Dosing consistency was defined as the probability of the device achieving a 'correct dosage' (CD) of 1.5–2.5 mg/L FRC at the kiosk's tap, balancing the minimum requirements of ≥ 0.2 mg/L after 24 h of storage and taste acceptability level (~2 mg/L). The following ratings were applied: Good ≥ 90 per cent, moderate ≥ 50 per cent, and poor < 50 per cent.

User-friendliness. If the operators reported that the device was easy to handle and did not express any complaints regarding its basic use (refilling chlorine products or adjusting chlorine dosage), the device received a good rating. If they reported difficulties or expressed a complaint regarding basic use (e.g. not easily accessible or the burden was beyond basic use), the rating attributed was moderate. If they were unable to use the device, the rating attributed was poor.

Ease of maintenance. If the device did not need to be repaired during the tests in the field, the rating attributed was good. If minor repairs had to be done that could be solved by the operator, the rating was moderate. If repairs could not be done by the operator or if any of the devices ceased to function, the rating attributed was poor.

Local supply chain. The following rating was applied regarding the local availability of the device and its spare parts: availability on the local market (LM) of Busia in eastern Uganda or in the neighbouring local market across the Kenyan border (rating = good), in the country's capital Kampala (= moderate) or it needs to be imported (= poor). Local availability was evaluated separately for chlorine products and hardware, including spare parts.

Cost. Calculations include the cost of the chlorine to achieve 2 mg/L FRC and the cost of the device, but no labour costs. We considered different device lifespans (1–5 years) and capacities (600–1,200 m^3/year). The current water price is UGX 50/jerry can ($0.013 = $0.66/$m^3$). Assuming 900 m^3 sold per year, a revenue of $592 would be generated. After deducting salary costs and maintenance expenses, 16 per cent of the yearly income ($93) would remain as profit. Under these assumptions, the cost of chlorinating the water cannot exceed $0.1/$m^3$ (rating = good). A rise in the water price to UGX 100/jerry can (= $1.32), as is common in other parts of Uganda, would enable a price of $0.59/$m^3$ for chlorination (= moderate). For higher chlorination costs, the rating attributed was poor.

Data collection and analysis

The chlorinators were consecutively installed as shown in Figure 1 and dosing was adjusted to ~2 mg/L. Four of the seven devices were extensively tested (CDB, T-chlorinator, Venturi, and AkvoTur). FRC concentrations were measured at least once per week over 1.5–2 months. On every data collection day, a sample was taken every 5–15 min over 2–6 hours to capture the fluctuation of flow rates.

The remaining three devices were tested less extensively. For the floater and the chlorine dispenser, samples were taken over 3–5 days during one week, and for the AquatabsFlo®, samples were taken over 0.5 h on two days. Flow rates were not recorded.

FRC was measured using a LaMotte DC1500-CL colorimeter and diethylphenylenediamine (DPD) tablets (LaMotte DPD1 TesTabs). Samples were taken at the tap of the GDM kiosks. The tap was opened, flushed for 10 seconds and a 10 ml vial was rinsed three times. Then, the sample was taken and immediately analysed. Samples from the chlorine dispenser were taken from the jerry can after the water was chlorinated and the jerry can was shaken.

To gain insight on user-friendliness, ease of maintenance, local supply chain, and costs, we 1) conducted qualitative interviews with the kiosk operators and staff from our local partner organization; 2) searched local markets for devices and consumables; and 3) evaluated observations of the research staff involved in the fieldwork. In addition, the operators were trained by our local partner organization to use the devices. The operators and NGO staff were informed about the goal, purpose, and methodology of the study and asked for informed consent. The study protocol was reviewed and approved by the Ethics Committee of Makerere University on 18 July 2018, the Uganda National Council for Science and Technology, and the Ethical Committee of Eawag, the Swiss Federal Institute of Aquatic Science and Technology on 6 June 2018.

Data was analysed using Excel and R-Studio. To test for normal distribution, histograms and one-sample Kolmogorov-Smirnov tests (two-sided) were used. FRC measurements were normally distributed ($p > 0.05$). The Pearson correlation coefficient (two-tailed) and linear regression models were used to explore the correlation between FRC concentrations and flow rate.

Results and discussion

Floater

The floater is commonly used to chlorinate swimming pools. In a technical manual, Luff (2001) mentioned the use of this device to chlorinate drinking water. However, the authors are not aware of any study that has assessed the floater's performance in chlorinating drinking water.

Our data indicates that the floater did not achieve consistent dosage ($\bar{x}$ = 1.5 mg/L ($\bar{x}$ = mean), SD = 0.9 mg/L, min = 0.1 mg/L, max = 3.1 mg/L, CD = 37 per cent, n = 15). During the analysis, the storage tank was constantly less than a quarter full. As the floater is placed in the storage tank, it is difficult to refill the tablets and to adjust the dosing. A positive factor, however, is that the floater is robust, available in Kampala and can be operated at low cost (~\$0.02/m^3). Yet, in the context of the GDM set-up, it is problematic to chlorinate the water from the inside of the storage tank as chlorinated water could flow back from the storage tank to the membrane tank and damage the membranes. Further studies are needed concerning the use of this device. Intermittent or variable flow also influences the dosing reliability because the contact time with the water varies.

Chlorine-dosing bucket (CDB)

The CDB was designed after observing challenges with the floater in the GDM set-up. The floater was integrated into an in-line device developed at Eawag. No similar use of a floater is known to the authors.

The CDB did not achieve consistent dosage ($\bar{x}$ =1.7, SD = 0.9 mg/L, min = 0.3 mg/L, max = 3.5 mg/L, CD = 40 per cent, n = 56, flow rate = 2.7–7.5 L/min). In a simple linear regression model, the flow rate and FRC concentrations were significantly correlated (R = –0.75, p = 0.003). To reduce the flow dependency, the proportion of water passing the bucket could be reduced or the size of the bucket increased. This is predicted by the steady state solution of the mass balance equation (Equation 1) and should be further researched. Some positive aspects are that the CDB is user-friendly, robust, can be made from low-cost locally available materials, and operated at low cost (≤ \$0.1/m^3).

$$C_{out} = \frac{k_{dissolution} \times V}{Q_1 + k_{decay} \times V} \times \frac{Q_1}{Q_{tot}} \quad (1)$$

where: C_{out} = FRC concentration after CDB [mg/L]
V = volume of the bucket of the CDB [L]
Q_1 = flow passing bucket [L/min]
Q_{tot} = total flow passing bypass and bucket [L/min]
k_{decay} = chlorine decay rate [L/min]
$k_{dissolution}$ = chlorine dissolution rate [mg/L*min]

T-chlorinator

The T-chlorinator assessed in this study is an adaption of the model looked at by Orner et al. (2017). They used the chlorinator in a gravity-fed piped distribution system. Compared to our study, the flow rate was substantially higher (60 L/min) and the target concentration substantially lower (0.27 mg/L).

In our assessment, the T-chlorinator achieved the best dosing consistency of all devices ($\bar{x}$ = 2.0 mg/L, SD = 0.3 mg/L, min = 1.1 mg/L, max = 3.0 mg/L, CD = 90 per cent, n = 64, flow rate = 3–8 L/min). No significant correlation between the flow rate and FRC concentration was found (R = –0.23, p = 0.070), which is consistent with Orner et al. (2017). The device is user-friendly and robust. The materials to build the device are inexpensive (~\$15) and available in Uganda, except for the required 1-inch chlorine tablets that need to be imported from Nairobi, Kenya. The operating costs (≤ \$0.05/m^3) are relatively low.

Venturi doser

The Venturi doser was developed by MSR, PATH, and Stanford University. The device has been extensively tested in the laboratory for flow rates of 10–40 L/min (SWAP, 2017). In field experiments, the device dosed consistently 1–1.5 mg/L (target concentration: 1 mg/L, flow rate 20–40 L/min, (SWAP, 2017)).

In our assessment, the dosing was less consistent for a flow rate of 6–20 L/min ($\bar{x}$ = 2.1 mg/l, SD = 0.7 mg/L, min = 0.2 mg/L, max = 3.3 mg/L, CD = 52 per cent, n = 58). For flow rates below 6 L/min, which sometimes occur at GDM kiosks, the WHO guideline value of 5 mg/L (WHO, 2017) was exceeded. No significant correlation between the flow rate and FRC (R = –0.3, p = 0.121) was observed. The operators were able to handle the Venturi doser. Even though the device is made of fragile parts, they are all protected in a robust metal box. No repairs were required. The device is still a prototype, is not available locally, and is relatively expensive ($150). Liquid chlorine is available locally (~$0.82/m^3) or can be self-produced (~$0.17–0.59/m^3), but at relatively high costs.

AquatabsFlo®

Pickering et al. (2019) assessed the AquatabsFlo® to chlorinate water at the point of collection and reported an average FRC concentration of 0.37 mg/L (SD = 0.32, target concentration: 0.2–0.5 mg/L, n = 2,335).

We found the dosing consistency to be moderate ($\bar{x}$ = 2.2 mg/L, SD = 0.6 mg/L, min = 1.7 mg/L, max = 3.6 mg/L, CD = 57 per cent, n = 8). However, the findings are based on only eight samples. Failure of the device to chlorinate (FRC ≤ 0.2 mg/L) was observed four times prior to data collection, and two times during data collection. Removing, shaking, and reinstalling the device restored FRC concentrations to ~2 mg/L. The two failed measurements were not included in the analysis. Adjusting the dosage with the provided screw was difficult. Furthermore, the device had to be removed from the kiosk's tap when the kiosk closed at night to prevent vandalism and frequent removal can damage the plastic bayonet catch. In other set-ups, the cartridge can be permanently installed *before* the storage tank, where it is better protected (Pickering et al., 2019). The device, including chlorine tablets, is available in Kampala. When the tablets are used up, the whole device has to be replaced. This leads to an increase in costs ($0.22/m^3 for 2 mg/L).

AkvoTur

The AkvoTur is similar to the AquatabsFlo®, but with a better mechanism to adjust dosage and the option to refill chlorine tablets. It was designed at Eawag.

The dosing consistency of the AkvoTur was moderate ($\bar{x}$ = 2.1 mg/L, SD = 0.5 mg/L, min = 0.8 mg/L, max = 3.6 mg/L, CD = 67 per cent, n = 78, flow rate = 2.5–9 L/min). No significant correlation between the flow rate and the FRC concentration was observed (R = 0.09, p = 0.436). The device cannot handle flow rates above 12 L/min, as this would cause overflow. The handling is similar to the AquatabsFlo®, but overdosing is possible if the cylinder containing the tablets is not positioned correctly. Like the AquatabsFlo®, the AkvoTur had to be removed daily from the kiosk's tap to prevent vandalism. The plastic threading suffers from the daily removal; therefore, the design needs improvements. Materials to produce the AkvoTur are available locally at low cost (~$7). As for the T-chlorinator, the 1-inch tablets need to be imported from Nairobi, Kenya.

Chlorine dispenser

Over 27,000 chlorine dispensers have been installed in Kenya, Uganda, and Malawi (Ahuja, 2017). Yates et al. (2015) studied dispenser programmes in four emergency situations. The programmes always employed a local promoter for community training. Confirmed dispenser use (FRC ≥ 0.2 mg/L in stored household water) ranged from 5 to 87 per cent.

Table 2 Evaluation matrix (white = good, grey = moderate, black = poor)

Device (price, US$)	*Dosing consistency*[1]	*User-friendliness*	*Ease of maintenance*	*Supply chain*		*Cost*[2] *(US$/m³)*	
				Chlorine	*Device and parts*		
Floater (~$7)	37% [1.5 ± 0.9 mg/L]	Difficult to refill	Robust, few wearing parts	3″ TCCA, Kampala	Kampala	0.01–0.02	
CDB (~$50)	40% [1.7 ± 0.9 mg/L] Flow dependent	Easy to use	Robust, few wearing parts	3″ TCCA, Kampala	Device can be made locally	0.02–0.10	
T-chlorinator (~$15)	90% [2.0 ± 0.3 mg/L]	Easy to use	Robust, few wearing parts	1″ TCCA, Nairobi, Kenya	Device can be made locally	0.02–0.05	
Venturi doser (~$150[3])	52% [2.1 ± 0.7 mg/L] Above 6 L/min	Easy to use	Fragile, but well protected parts	NaOCl, LM[5] or SP[6]	Prototypes from USA	0.85–1.07 (LM[5])	0.18–0.82 (SP[6])
AquatabsFlo® (~$20[4])	57% [2.2 ± 0.6 mg/L] chlorination failure occurred	Daily installation needed	Not durable, device needs replacement with tablets	NaDCC, Kampala	Kampala	0.22	
AkvoTur (~$7)	67% [2.1 ± 0.5 mg/L] Up to 12 L/min	Daily installation needed; overdose possible	Not durable, wearable parts	1″ TCCA, Nairobi, Kenya	Device can be made locally	0.02–0.03	
Dispenser (~$20)	52% [1.9 ± 0.7 mg/L] 6 ml NaOCl per jerry can	Easy to use	Robust, few fragile parts	NaOCl, LM[5] or SP[6]	Kampala	0.96–0.99 (LM[5])	0.18-0.63 (SP[6])

Note: [1] Probability to achieve 1.5–2.5 mg/L [mean FRC ± SD]; [2] chlorination to 2 mg/L for a device lifespan of 1–5 years and production of 600–1,200 m³/year; [3] estimated product price if mass produced according to MSR; [4] including chlorine tablets; [5] local market; [6] self-produced

The dispenser releases 3 ml of NaOCl per turn of the ball valve. In our assessment, one turn provided a mean 0.9 mg/L in a 20 L jerry can (SD = 0.2 mg/L, min = 0.5 mg/L, max = 1.3 mg/L, n = 27), and two turns 1.9 mg/L (SD = 0.7 mg/L, min 0.6 mg/L, max = 3.9 mg/L, CD = 52 per cent, n = 17). The device is easy to use, robust, and available in Kampala at ~$20. The liquid chlorine is available locally at ~$0.96/m^3 or can be self-produced (~$0.17–0.59/m^3). As users have to chlorinate the water themselves, it is likely that the water would not always be chlorinated before consumption. This was confirmed by observations of the operator, as well as by Yates et al. (2015). The dependence upon user compliance is a significant disadvantage of the chlorine dispenser. Table 2 summarizes the assessment of the different chlorination devices.

Limitations

Due to how the data collection in the field was done, the number of samples taken for FRC measurements of the different devices vary. While the sample sizes for AquatabsFlo® (n = 8), the chlorine dispenser (n = 27), and the floater (n = 15) are limited, they are much larger for the other devices (n = 56–78). As the sample size increases, the sampling distribution clusters more tightly around the mean and, consequently, the standard deviations shrink. Therefore, our results might overestimate the standard deviation of the devices with small sample sizes.

Conclusion and recommendations

Seven low-cost, non-electrically powered chlorinators were assessed at GDM water kiosks in eastern Uganda. Dosing consistency was challenging. Only the T-chlorinator had a probability ≥ 90 per cent to achieve the target concentration of 1.5–2.5 mg/L FRC at the tap. The probabilities of reaching the target concentration of the AkvoTur, the Venturi doser, the AquatabsFlo®, and the chlorine dispenser were 52–67 per cent, and of the floater and the CDB <40 per cent.

All the devices assessed were user-friendly and easy to maintain, except for the floater, which is difficult to refill, and the tap-attached options AkvoTur and AquatabsFlo®, which need to be removed daily in the GDM set-up to prevent vandalism. Because of the daily removal of these devices, the risk of damage during handling is increased. In other set-ups, these devices can be installed *before* the clean water tank, and are, therefore, better protected (Pickering et al., 2019). The Venturi doser is also attached to the tap, but it is robust and can be permanently installed. The findings of the Venturi doser, however, indicate inconsistent dosing when flow rates drop below 6 L/min.

All the devices or parts needed to construct them, as well as chlorine products, are available in Uganda or the border town in Kenya that is 1 km away, except for the Venturi doser and the 1-inch TCCA chlorine tablets. In the calculated scenarios (600–1,200 m^3 chlorinated water/year over 1–5 years), the chlorination costs of the tablet-based options were ≤ $0.1/m^3 and could be covered by the revenues of

the kiosk. The only exception was the AquatabsFlo® ($0.22/m^3). The costs of the liquid chlorine-based options were between $0.18 and $1.07/m^3 and could not be covered by the revenues of the kiosk given the current water price ($0.66/m^3). Adding the cost for liquid chlorination to the water price, therefore, would have a significant impact on the business model.

Overall, the T-chlorinator performed best in our assessment for the GDM kiosks, which are characterized by low pressure (2–30 kPa), a variable and low flow rate (3–24 L/min), and no possibility to install the tap-attached options in a safe place. However, the required 1-inch TCCA tablets need to be imported from Nairobi, Kenya.

The chlorine dispenser is the only option where users have to chlorinate the water manually themselves. Establishing a consistent practice to do so on the part of users has been found to be difficult (Yates et al., 2015), but is critical for health improvements (Hunter, 2009; Brown and Clasen, 2012; Enger et al., 2013). Therefore, the chlorine dispenser can only be recommended if user compliance were high.

Even though the GDM kiosks in this study have a specific design, general recommendations can be drawn from our experience.

1. If the chlorine demand of the water is high (> 1.3 mg/L over 24 h), it may be difficult to find a chlorinator that consistently (≥ 90 per cent) guarantees ≥ 0.2 mg/L FRC after 24 h of storage and at the same time does not interfere with taste acceptability (~2 mg/L). In this case, measures to reduce the chlorine demand are recommended; for example, safe storage containers (Roberts et al., 2001; Reed et al., 2011; Mellor et al., 2013; Gärtner et al., 2020) or periodically cleaning and disinfecting the containers (Steele et al., 2008; Meierhofer et al., 2019; Gärtner et al., 2020).
2. The installation of in- or end-line chlorination options offers a potential solution to circumvent the challenge of establishing consistent and correct manual chlorine dosing by the user. However, low-pressure systems and variable flow rates pose challenges to the dosing consistency of many in- and end-line chlorinators. Further developing these kinds of devices to improve their performance is required.
3. The establishment of a reliable and affordable supply chain for the chlorine products suitable for drinking water treatment may be challenging. Yet, it is a key factor for the sustainable operation of chlorination devices.

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