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RESEARCH ARTICLE

Assessment of a local and low-cost passive in-line chlorination device in rural Guatemala

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Abstract

Access to safe and affordable drinking water remains a major challenge worldwide, especially in rural areas. While passive in-line chlorination offers a promising approach for providing consistent treatment of water supplies in resource-limited settings, little is known about the factors influencing the uptake and use of these technologies. This study used a controlled pre-post intervention design to evaluate the technical performance and user acceptance of a low-cost and locally constructed chlorinator (the A'Jín) in four water distribution systems in rural Guatemala. Data sources included household surveys (N = 319) and operator interviews (N = 25), with regular monitoring of faecal contamination, pH, temperature and free residual chlorine (FRC) at reservoir tanks, taps and households. Faecal contamination was significantly reduced in water systems actively using the A'Jín device. In these systems, the share of tap and household drinking water samples with detectable *E. coli* decreased from 28% to 1% and 25% to 15%, respectively. Chlorine dosing consistency with the A'Jín was low, with only 24% of tap samples meeting the recommended minimal FRC threshold of 0.2 mg/L. Overall, the share of users expressing satisfaction with their water increased by 14% in the water distribution systems with the A'Jín and stayed constant for users of control systems. While the device's low cost and simple design offered advantages over other chlorinators on the market, operators reported challenges with high maintenance needs and frequent clogging. To ensure the future success of passive in-line chlorination for small community supplies, we recommend prioritising ease of use combined with external support for addressing maintenance needs.

Introduction

The world is not on track to achieve the United Nation's Sustainable Development Goal (SDG) Target 6.1 to ensure universal and equitable access to safe and affordable drinking water for all [1]. Two billion people still lack access to a reliable and readily accessible water

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Competing interests: I have read the journal's policy and the authors of this manuscript have the following non-financial competing interests: 1. Giezy Sanchez and Nexan Herrera are employed by Helvetas-Guatemala, which developed the design for A'Jín chlorinator. However, the design is provided freely online and the organization receives no financial benefit based on the results of this study. 2. Sara Marks serves as an academic editor for PLOS Water.

source free from contamination, mainly localized to rural areas [2]. Unsafe drinking water is one of the principle risk factors for diarrhoeal diseases, the second leading cause of child (< 5 years old) deaths globally [3, 4].

The main strategy to reduce waterborne pathogen contamination in rural areas where effective centralised treatment is not available has been point-of-use (POU) treatment [5]. POU options include boiling, solar disinfection, and chlorination (alone or combined with flocculation-sedimentation) and ceramic or sand filters. For example, the *Ecofiltro*, a ceramic drinking water filter, has proven successful in reducing microbial contamination in household drinking water of rural Guatemala and Honduras [6, 7]. However, widespread and sustained adoption of POU methods has proven difficult due to the necessary behaviour change at the household level [8–11]. To address these challenges, the World Health Organisation (WHO) recommends a gradual shift towards professionalized operation and management of small water supplies through a step-wise supported process [12, 13].

A promising alternative to POU treatment is passive in-line chlorination of water distribution systems (WDS) prior to the point of collection (POC) [14–16]. It reduces the burden of treatment at the household level, a duty that falls most often to women, who play a crucial role in household water management [17]. However, while passive chlorination does not necessarily require electricity or daily user input, there is still a need for active operation and management efforts to refill chlorine and ensure consistent and correct dosing.

While the use of chlorine is advantageous due to its residual disinfection capacity even after collection [18, 19], it has several limitations that can reduce its efficacy. For instance, it has limited effectiveness against certain parasites such as Giardia and *Cryptosporidium* [20]. Effective chlorine disinfection can also be greatly influenced by a variety of other factors, including the free residual chlorine (FRC) concentration, contact time, pH, ammonia concentration, natural organic matter (NOM) content and water temperature [21]. The pH is especially important as it influences the speciation of aqueous chlorine from hypochlorous acid (HOCl) to hypochlorite (OCl^-), with HOCl being approximately 80 times more effective as a disinfectant than OCl^-. Temperature also plays a role, with lower temperatures causing this reaction to occur at slightly higher pH values [21, 22]. Hence, there are a number of factors that must be regularly monitored in order to optimally implement chlorination devices.

A variety of commercial passive in-line chlorinators have been implemented in various settings, and their effectiveness has been assessed. Crider et al. evaluated the Aquatabs Flo and PurAll 100 devices for gravity-fed piped supplies in rural Nepal and found that both technologies were effective solutions for improving the microbial safety of collection taps [23]. Lindmark et al. composed a review of passive in-line chlorination technologies and identified the challenges faced in their implementation to be the viability of the business models, compatibility with existing infrastructure, the consistency and accuracy of chlorine dosing and unreliable access to high-quality chlorine supplies [16]. While several studies have identified key challenges for implementing in-line chlorination at scale, there has been relatively little research on the interplay amongst these factors. For example, little is known about how operators' perceptions and experiences with in-line chlorination are influenced by its design and how these factors subsequently influence its uptake and use.

To address this lack of information about deployed interventions, the planned roll-out of the A'Jín chlorinator, a low-cost, locally constructed, passive chlorination device for system-level disinfection, presented the opportunity for a holistic evaluation from both technical and user-centred perspectives. This A'Jín chlorinator was piloted by the NGO Helvetas Guatemala through the ongoing project named RU'K'UX YA', which delivers water and sanitation improvements in collaboration with the municipal office of water and sanitation (OMAS) in the department of Sololá in rural Guatemala. Their work is important, as Guatemala has among the highest rates of chronic malnutrition and child morbidity in Latin America [24], and only 56% of Guatemalans had safely managed drinking water services as of 2020 [1, 2]. As the NGO Helvetas Guatemala identified a critical need for reliable system-wide treatment of rural drinking water supplies, the initial pilot of the A'Jín device established its technical viability for delivering in-line chlorination at scale. However, questions remain regarding its acceptance, uptake and use across the RU'K'UX YA' service area.

Thus, the objectives of this study were to: (1) evaluate the technical performance of the A'Jín device to consistently dose chlorine and reduce bacterial contamination of tap (point-of-collection) and household drinking water, (2) assess system operators' perceptions and experiences with passive chlorination in the context of existing system management practices in rural Guatemala, and (3) assess water users' perception, acceptance, and behaviour changes due to chlorination of the WDS. These findings will provide a more holistic understanding of the inter-related factors affecting the uptake and use of in-line chlorination technologies.

Materials and methods

Study setting and design

Rural communities in the department of Sololá are predominantly agrarian with 81% of the population living below the poverty line and 40% living in extreme poverty [25]. Most communities have piped gravity-driven WDS that directly distribute water from protected spring sources to households via a reservoir tank without centralised treatment, as depicted in Fig 1. Some WDS have multiple spring sources and/or reservoir tanks. Each WDS is governed by a communal water board committee responsible for its operation and maintenance.

However, many communities face unreliable water availability, inconsistent monitoring and vulnerability to faecal contamination [26, 27]. This study involved a collaboration between Eawag and Helvetas Guatemala, the latter being involved in the RUK'U'X YA' program. RU'K'UX YA' means "the heart of the water" in the Maya language Kaqchikel. This program ran from 2020–2023 and aimed to enhance WDS and sanitation facilities, raise awareness about health risks, and provide governance support for 1 WDS in the Sololá department. The program was funded by the Spanish Agency for International Development Cooperation (AECID) and is managed by Helvetas Guatemala and the NGO Action Against Hunger (in Spanish: Acción contra el Hambre).

A controlled before-and-after study design was used to evaluate the performance of the A'Jín device. A WDS was eligible for enrolment in the study if they were actively participating in the RUK'U'X YA' program and agreed to ongoing water quality monitoring of their water supply for the duration of the 6-month study period. A total of 14 WDS met these criteria and were offered enrolment in the study. Five WDS opted in to chlorination, meaning the user assembly agreed to adopt chlorination using the A'Jín device (hereafter referred to as treatment WDS). Nine WDS opted out of chlorination with the A'Jín (hereafter referred to as control WDS). The study collected data before installing the A'Jín device (baseline) and after its installation and use (endline). Additionally, four WDS (2 control, 2 treatment) were monitored in greater detail over eight visits to gather device performance data on a more granular time scale. The same water quality measurements and in-person interviews were conducted across all the WDS under investigation. The study flow chart is shown in Fig 2.

A'Jín chlorinator

The recommended minimum FRC concentration at point of consumption, per international guidelines, is 0.2 mg/L [28]. Guatemalan standards define the maximum acceptable limit for FRC at the point of consumption as 0.5 mg/L and the maximum permissible limit for FRC as 1

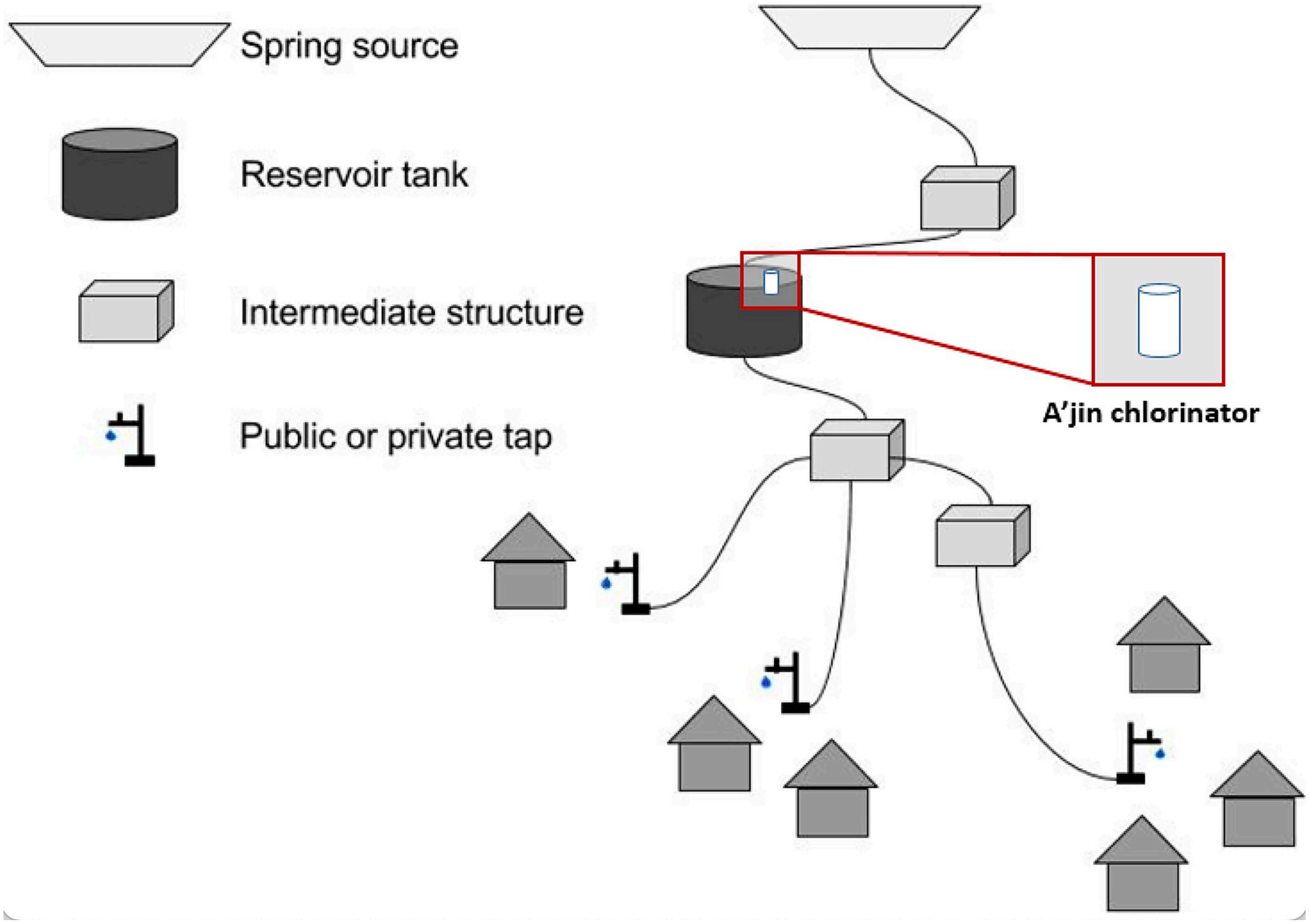

Fig 1. Schematic of a typical gravity-fed piped water distribution system (WDS). The A'J´ın chlorinator can be installed at reservoir tank level without any necessary structural adaption of the WDS. Adapted from Tosi Robinson et al. (2018), https://doi.org/10.3390/ijerph15081616 [44].

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mg/L [29]. The A'Jín chlorinator was developed by Helvetas Guatemala to allow for manual construction using PVC parts locally available in hardware stores (S4 Fig) [30], and it can be installed at the reservoir tank by connecting it to a bypass pipe via a T-junction (Fig 3, S5 Fig). This in-line erosion chlorinator consists of the main body, a screwable lid, an inlet and outlet ball valve, and a holder for solid tablets of calcium hypochlorite, which have to be refilled manually. As water moves through the device, it slowly dissolve and mixes with the tablets through holes in the chlorine tablet holder. An initial dosage setting is estimated by counting the number of drops falling into the reservoir tank per minute in order to reach the desired free chlorine concentration. The drop rate is adjusted by opening or closing the inlet and outlet valves and thus increasing or decreasing the flow rate through the chlorinator and calibrating the inner water level. The construction cost of the device is 70 USD, and the material cost required for installation is approximately 32 USD [31]. No prior published evaluations of this technology were identified. Further details on the A'Jín chlorinator are provided in S2 Text.

Data sources

Household survey. With the support of the water board committee members present during the baseline visit, each WDS was split in three sectors based on proximity to the reservoir

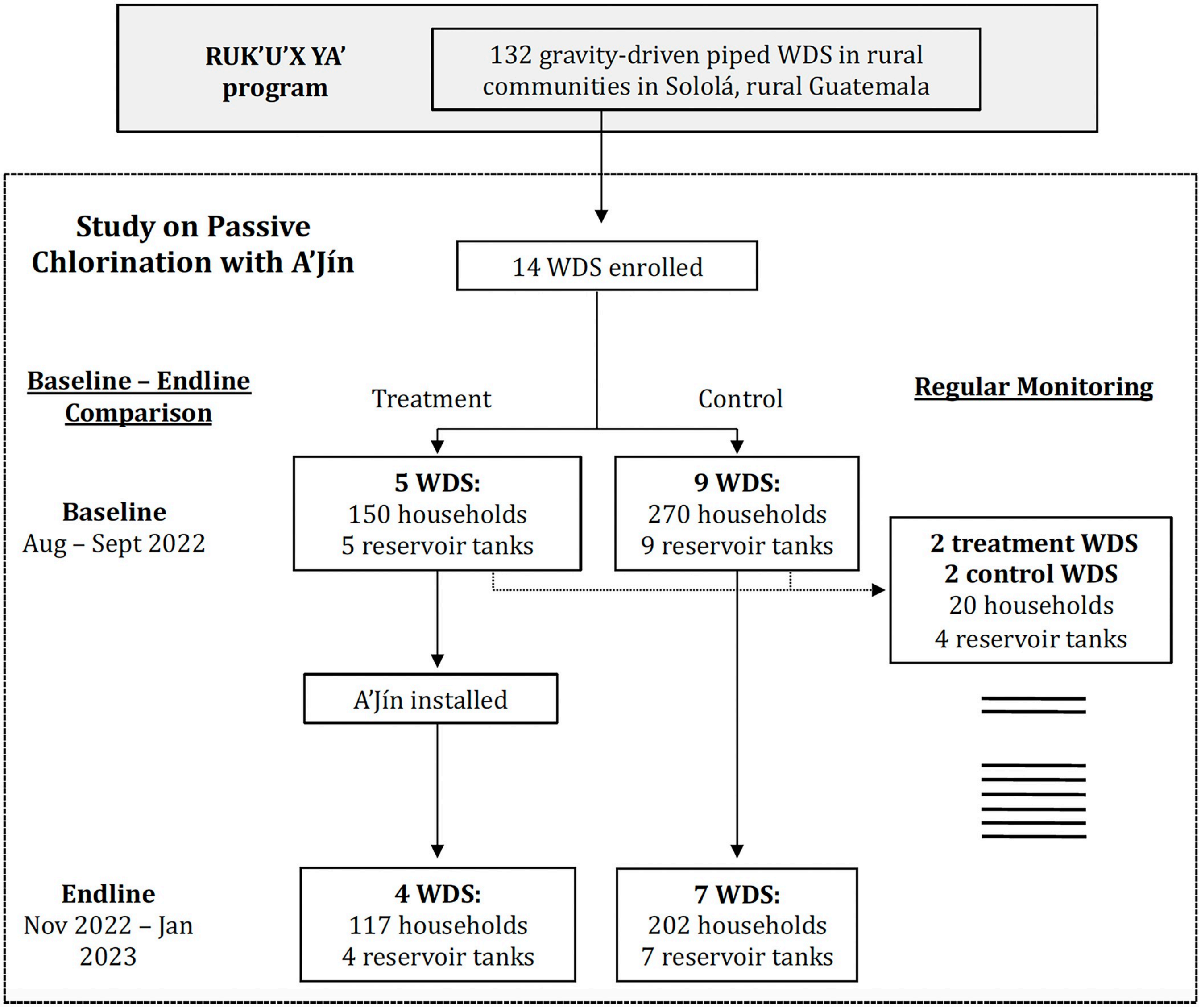

Fig 2. Study flow chart. Each WDS consisted of a reservoir tank and a piped distribution network with household and public taps. Three WDS dropped out of the study before the endline visit.

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tank: close to the reservoir tank, middle sector, and end of the WDS. Ten households from each sector were enrolled by selecting approximately one from every five for a total of 30 across the WDS. Households were eligible for enrolment if they consumed the tap water of the WDS as their main drinking source. Surveys of approximately 30 minutes were conducted in Spanish or Kaqchikel using the Kobo Toolbox open-source mobile software on either tablets or smartphones.

The surveys probed household characteristics, water treatment and storage practices, perceptions regarding water safety, and perceptions and acceptance of chlorination. Each household was assigned a unique ID, and the same household was visited for a follow-up survey at endline. If the same person was not present at the second visit, another available household member with water management responsibilities was interviewed. If no one was available for

Fig 3. Installed A'Jín chlorinator in one of the WDS enrolled in the study. The T-junction guides the water at tank inlet to the chlorinator, the valves determine the chlorine drop rate falling into the reservoir tank. Photo credit: Helvetas Guatemala.

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the interview during the second visit, data collection was attempted at a neighbouring household that was accessible and willing to participate.

Operator survey. During the baseline and endline visit, a WDS operator survey was conducted with one water committee member. The survey included questions about the members' working experience as part of the water committee, the operation and breakdowns of the WDS, governance practices, the experience of chlorination with the A'Jín device (if applicable), and general information about the WDS and its water source. In treatment WDS, observations of the chlorinator functionality, issues confronted, and the presence or absence of chlorine tablets in the chlorinator were documented.

Water quality sampling. To evaluate the performance of the A'Jín chlorinator in disinfecting the water of the distribution system, water samples were collected in each enrolled household during the baseline and endline visit. To evaluate the impact of chlorination on the drinking water the household consumes daily, the study team requested the following before collecting the sample: "Please show me how you would serve yourself water to drink it." Drinking water samples were thus collected from any possible container (bottle, pan, glass) or source (tap, table-top filter). Additionally, a sample from the reservoir tank of each WDS was taken. All collected samples were assessed for pH, temperature, and FRC concentration. No upstream samples could be collected, as neither the spring sources nor the inlet pipe of the reservoir tank were accessible. The WDS that were actively chlorinating at the endline visit were placed into a subgroup of *"actively chlorinated WDS"* to assess the technical performance of the A'Jín for water disinfection. Only households sampled during both baseline and endline were included in the baseline-to-endline comparison analysis. Water quality results were compiled on tablets using the mWater software platform (New York, USA) and linked to households' unique IDs in an Excel database.

For additional testing in four enrolled WDS, namely two controls (WDS 4 and 6) and two treatments (WDS 3 and 9), five households were randomly selected for eight regular monitoring visits in between the baseline and endline phases. Two of the visits took place before the installation of the chlorinator and six during the weeks following the installation. Monitoring activities included sample collection from household drinking water, tap water, and reservoir tanks to assess bacterial levels, pH, temperature and FRC. Observations about the functioning of the chlorinator were noted. No in-person interviews were conducted during regular monitoring visits.

Sample collection and microbial testing

All water samples were collected with Whirl-Pak sample bags with a capacity of 118 mL (4 oz); when the presence of chlorine was suspected, Whirl-Pak Thio-Bags (Nasco, Fort Atkinson, USA) were used. Drinking water samples were collected directly from their container. For tap samples, the tap was flamed with a lighter and the water run for 30 seconds prior to sample collection. If the water surface was accessible, reservoir tank samples were collected directly with a Whirl-Pak bag dipped into the tank. Otherwise, the sample was collected with a sterile stainless-steel cup connected to a piece of cord (DelAgua, UK). Temperature, pH and FRC were measured on site (HI98107 pHep digital pH and temperature tester, HI701 Free Chlorine Digital Colorimeter, Hanna Instruments Inc, Woonsocket, USA).

Directly after collection, the samples were stored in portable cold boxes containing ice packs for a maximum of 5 hours for transport to the Laboratory for Water Quality of Santa Lucía Utatlán (Health Ministry of Guatemala). There, they were either processed the same day or stored in a refrigerator at 5 ± 2°C for a maximum of 24 hours and processed the following day. The samples were left to rest at ambient temperatures for 15 minutes before processing with membrane filtration. Two filtration devices were used in parallel: the DelAgua portable filtration funnel with a manual vacuum pump and disinfection with methanol (DelAgua, UK) [32] and a three branch filtration funnel manifold with a vacuum pressure pump and disinfection with ethanol. All water samples were filtered through membrane filters with a 47 mm diameter and 0.45μm pore size and placed on Petri-pad dishes containing m-ColiBlue24-Bouillon growth medium (MilliporeSigma, Burlington, USA). After filtration, the petri dishes rested at ambient temperature for a minimum of 10 minutes before incubation for 24 hours at 35 ± 2°C. The incubator models were Thermo Scientific Incubator model 658 (Thermo Fischer Scientific, Switzerland) and Model 12E Incubator (Quincy Lab Inc, Burr Ridge, USA). Further details on the filtration method can be found in the technical information sheet S1 Text. One negative and one positive control were processed daily for each filtration set up, and 5% of samples had a duplicate processed. Further details on quality assurance are found in S1 Table and S2 Text.

Data analysis

Water quality and survey data were compiled and cleaned in Excel 16.0 (Microsoft, Redmond, WA, USA). To convert costs to USD, we used the May 15, 2023, exchange rate of 1 USD = 7.8 Guatemalan Quetzales (GTQ). Water quality data were censored to indicate the lower limit of detection (LLOD) and upper limit of detection (ULOD) for each method used to assess temperature (LLOD = 0°C, ULOD = 50°C), FRC (0.05 ppm, 2.5 ppm) and bacterial contamination (<1 CFU/100 mL, 200 CFU/100 mL). Bacterial counts of < 1 CFU/100 mL were assigned a value of 0.5 for log transformation. Statistical analyses were performed with RStudio version 4.2.3. ChatGPT (OpenAI, San Francisco, CA, USA) was used in selected incidences to troubleshoot the R code. Bacterial contamination data were log-transformed but still did not meet the assumptions for parametric statistical tests. Therefore, the non-parametric Wilcoxon signed-rank test was used for bivariate comparisons of baseline and endline concentrations of *E. coli* and total coliform.

A difference-in-difference analysis was used to isolate the effect of the chlorination intervention from other factors potentially influencing *E. coli* contamination levels over time. This analysis was performed for both tap and drinking water samples and only included actively chlorinated WDS, defined as the subset of WDS that reported using the chlorinator and had detectable chlorine during the endline visit.

Ethics

Prior to enrolment in the study, verbal informed consent was obtained from all study participants. Verbal consent was preferred over written consent because literacy levels varied widely among study participants. The consent script included explanation of the purpose, scope, potential risks, expected benefits and the planned timeline of activities. Participants were given the option to opt out of participating at any time and were provided with the phone number of the local team manager who could be contacted with concerns. The study protocol, including the verbal consent procedure, received ethical approval from the Bioethics Committee for Health Research at the University of San Carlos of Guatemala (Ref. 003–2021, date: 21 April 2021) and from Eawag's internal ethical review committee (Protocol No. 16–09 2022 07 22).

Results

At baseline, (August to September 2022) data were collected from 9 control and 5 treatment WDS, supplying 420 households and 14 reservoir tanks (Fig 2). Three WDS dropped out of the study after the baseline phase due to the their WDS user assemblies declining to participate in continued monitoring visits. Thus, at endline, (November 2022 to January 2023) data were collected from 7 control and 4 treatment WDS, supplying 319 households and 11 reservoir tanks. Due to a lack of availability of chlorine tablets, one treatment WDS had not been operating the A'Jín chlorinator for over two weeks, and no FRC could be detected in the tap water at endline. Thus, in addition to the initial study choice of "treatment" and "control" WDS, we created the subgroup "actively chlorinated" WDS, which included only the three that were actively operating the A'Jín at the endline visit.

Household characteristics

Nearly all households interviewed were Indigenous Kaqchikel (99%), with the remainder being of Spanish descent. The average household size was six members. The highest level of education was reported as primary education for approximately half of the heads of household, regardless of gender (54% for males and 53% for females). Agriculture was reported as the main income source for about half (48%) of households, while other common occupations were small business owner (12%) and daily labourer (9%). Regular monthly expenditures for basic necessities (food, rent, clothing, transport) was less than 1000 GTQ (128 USD) for 34% of households, 1000–2000 GTQ (128–256 USD) for 42% of households, 2000–3000 GTQ (256–384 USD) for 15% of households, and over 3000 GTQ (384 USD) for 7% of households. The most frequently reported concerns (unprompted) were water supply services (22%), followed by health and health services (17%), sanitation and hygiene (17%), unemployment (11%) and transport and roads (10%). See S3 Table for more detail.

Water distribution system characteristics

On average, the 14 enrolled WDS each had 159 connected households (SD = 150, min = 43, max = 620). All WDS used spring sources, with three WDS relying on pumps and 11 solely on gravity to transport the water to the reservoir tank. In the zone 200 m above the spring source, seven of the 14 systems reported forest coverage, two reported animal pastures, four reported settlements and six reported agriculture activities. Ten WDS experienced an interruption in water service of >1 day duration in the past 6 months, as reported by the system operator. Among these 10 systems, the interruptions happened an average of 5 times (SD = 6, min = 1, max = 20) over the 6-month period. More than half of these interruptions were due to pipe breaks, and the rest were due to a broken pump, lack of water at the source, and maintenance work (see S4 Table for further information on WDS characteristics).

Water quality

Tap samples. Table 1 provides an overview of the baseline and endline water quality results. The mean pH level was 7.2 (SD = 0.5) at baseline and 7.3 (SD = 0.5) at endline, with 94% and 95% of samples lower than pH 8, respectively. At baseline, 28% of all tap samples were positive for *E. coli* and 78% were positive for total coliforms. At endline, 5% of control tap samples and 13% of treatment tap samples were positive for *E. coli*. From the actively chlorinated WDS tap samples, only 1% were contaminated with *E. coli* at endline. Among all tap samples, 65% of control samples and 59% of treatment samples had detectable total coliforms at endline. From the actively chlorinated tap samples, 47% were contaminated with total coliforms at endline. From actively chlorinated WDS, FRC was detectable (> 0.05 ppm) in 41% of tap samples at endline. From these samples, 100% were free of *E. coli* and 57% were free of total coliforms. Of the actively chlorinated WDS samples, the mean FRC was 0.25 ppm (SD = 0.36), and 38% had FRC values above 0.1 ppm, 24% were between 0.2 ppm and 0.5 ppm, and 9% were above 0.5 ppm.

For all WDS groups (control, treatment, and actively chlorinated), there was a significant (Wilcoxon signed rank test, $p<0.05$) decrease in *E. coli* $\log_{10}$ and total coliform $\log_{10}$ concentrations from baseline to endline. Consequently, there was a decrease in the health risk for each group from baseline to endline (Fig 4). The control group had a 14 percentage point increase in the share of tap water samples categorised as low risk (<1 CFU/100 mL). By comparison, the actively chlorinated group had a 27 percentage point increase in the share of low risk tap samples. At endline, 99% of the samples of this group were considered low risk and 1% were considered high risk (11–100 CFU/100 mL).

The total decrease in *E. coli* in actively chlorinated WDS tap samples was 0.516 $\log_{10}$ CFU/100 mL, equivalent to a 70% reduction in contamination (Table 2). A difference-in-difference analysis found that chlorination alone resulted in a decrease of 0.432 $\log_{10}$ CFU/100 mL for *E. coli*, equivalent to a 63% reduction in contamination (SE = 0.074, t = 5.846, $p < 0.001$). Therefore, chlorination was uniquely responsible for 91% of the overall reduction in faecal contamination in tap samples, with the remaining decline due to overall water quality trends. Similarly, there was an overall decrease in total coliform of 0.960 $\log_{10}$ CFU/100 mL in tap samples, equivalent to an 89% reduction in contamination. Chlorination alone resulted in a decrease in total coliform of 0.715 $\log_{10}$ CFU/100 mL, equivalent to an 81% reduction in contamination in absolute terms (SE = 0.166, t = 4.322, $p < 0.001$) and accounting for 91% of the overall reduction in total coliforms.

Reservoir tank samples. In reservoir tank samples, the mean pH level was 7.1 (SD = 0.4) at baseline and 7.2 (SD = 0.5) at endline, with 100% and 91% of samples lower than pH 8 at each timepoint, respectively. At baseline, 36% of the samples were contaminated with *E. coli* and 82% were contaminated with total coliforms. The mean baseline *E. coli* concentration for

Table 1. Tap and tank water quality results for baseline and endline visits [a].

	Combined N = 11	Control N = 7			Treatment N = 4			Actively Chlorinated N = 3		
	baseline	**baseline**	**endline**	**Wilcoxon signed rank test**	**baseline**	**endline**	**Wilcoxon signed rank test**	**baseline**	**endline**	**Wilcoxon signed rank test**
Tap water	n = 309	n = 198	n = 198		n = 111	n = 111		n = 86	n = 86	
E. coli present	0.28	0.19	0.05		0.43	0.13		0.28	0.01	
Total coliform present	0.78	0.80	0.65		0.76	0.59		0.69	0.47	
E. coli log10 [log10 CFU/ 100 mL]	0.09 (0.80)	-0.19 (0.29)	-0.27 (0.14)	V = 958 p<0.001[b]	0.59 (1.11)	-0.20 (0.23)	V = 1261 p<0.001 [b]	0.23 (0.92)	-0.29 (0.14)	V = 318 p<0.001 [b]
Total coliform log10 [log10 CFU/100 mL]	1.16 (0.95)	1.00 (0.82)	0.73 (0.96)	V = 10726 p = 0.006[b]	1.44 (1.10)	0.69 (1.07)	V = 2715 p<0.001 [b]	1.21 (1.15)	0.28 (0.81)	V = 1983 p<0.001 [b]
FRC [mg/L]	-	-	-		-	0.19 (0.32)		-	0.25 (0.36)	
Detectable FRC (above LLOD)	-	-	-		-	0.34		-	0.41	
0.2 mg/L < = FRC < 0.5mg/L	-	-	-		-	0.19		-	0.24	
FRC > = 0.5 mg/L	-	-	-		-	0.07		-	0.09	
pH	7.24 (0.51)	7.28 (0.54)	7.28 (0.55)		7.15 (0.44)	7.13 (0.49)		7.08 (0.40)	7.27 (0.53)	
Reservoir water	n = 11	n = 7	n = 7		n = 4	n = 4		n = 3	n = 3	
E. coli present	0.36	0.29	0.00		0.50	0.00		0.33	0.00	
Total coliform present	0.82	0.86	0.71		0.75	0.75		0.67	0.67	
E. coli log10 [log10 CFU/ 100 mL]	0.09 (0.81)	-0.22 (0.15)	-0.30 (0.00)		0.64 (1.23)	-0.30 (-)		0.57 (1.50)	-0.30 (0.00)	
Total coliform log10 [log10 CFU/100 mL]	1.18 (0.85)	1.12 (0.76)	1.18 (1.05)		1.29 (1.12)	0.90 (0.85)		1.15 (1.33)	0.64 (0.83)	
FRC [ppm]	-	-	-		-	0.70 (1.05)		-	0.91 (1.18)	
pH	7.06 (0.49)	6.97 (0.64)	7.09 (0.22)		7.20 (0.08)	7.38 (0.70)		7.20 (0.10)	7.33 (0.85)	

[a] All values are mean (standard deviation) and the unit is proportion of samples if not specified otherwise

[b] p-value < α, indicating statistical significance

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all reservoir samples was 0.09 log$_{10}$ CFU/100 mL (SD = 0.81). At endline, all reservoir tank samples (control, treatment, actively chlorinated WDS) were free of *E. coli* contamination.

Household drinking water samples. In collected household water drinking samples, the mean pH level was 7.5 (SD = 0.6) both at baseline and at endline. At baseline, 15% of control and 25% of treatment drinking water samples had detectable *E. coli*. At endline, 11% of control and 15% of treatment samples had detectable *E. coli*. From the actively chlorinated WDS, 8% were contaminated with *E. coli*.

At endline, FRC was detectable (>0.05 ppm) in 20% of drinking water samples from actively chlorinated WDS, with a mean value of 0.12 ppm (SD = 0.24). Of these actively chlorinated samples, 17% had FRC values above 0.1 ppm, 9% were between 0.2–0.5 ppm and 3% were above 0.5 ppm. From these samples, 88% were free of *E. coli* and 18% were free of total coliform contamination. There was a significant (Wilcoxon signed rank test, $p<0.05$) decrease in *E. coli* log$_{10}$ concentration from baseline to endline for household samples in treatment WDS but not for control WDS. Conversely, there was a significant decrease in total coliform log$_{10}$ concentration in control drinking water samples but not for treatment nor for actively

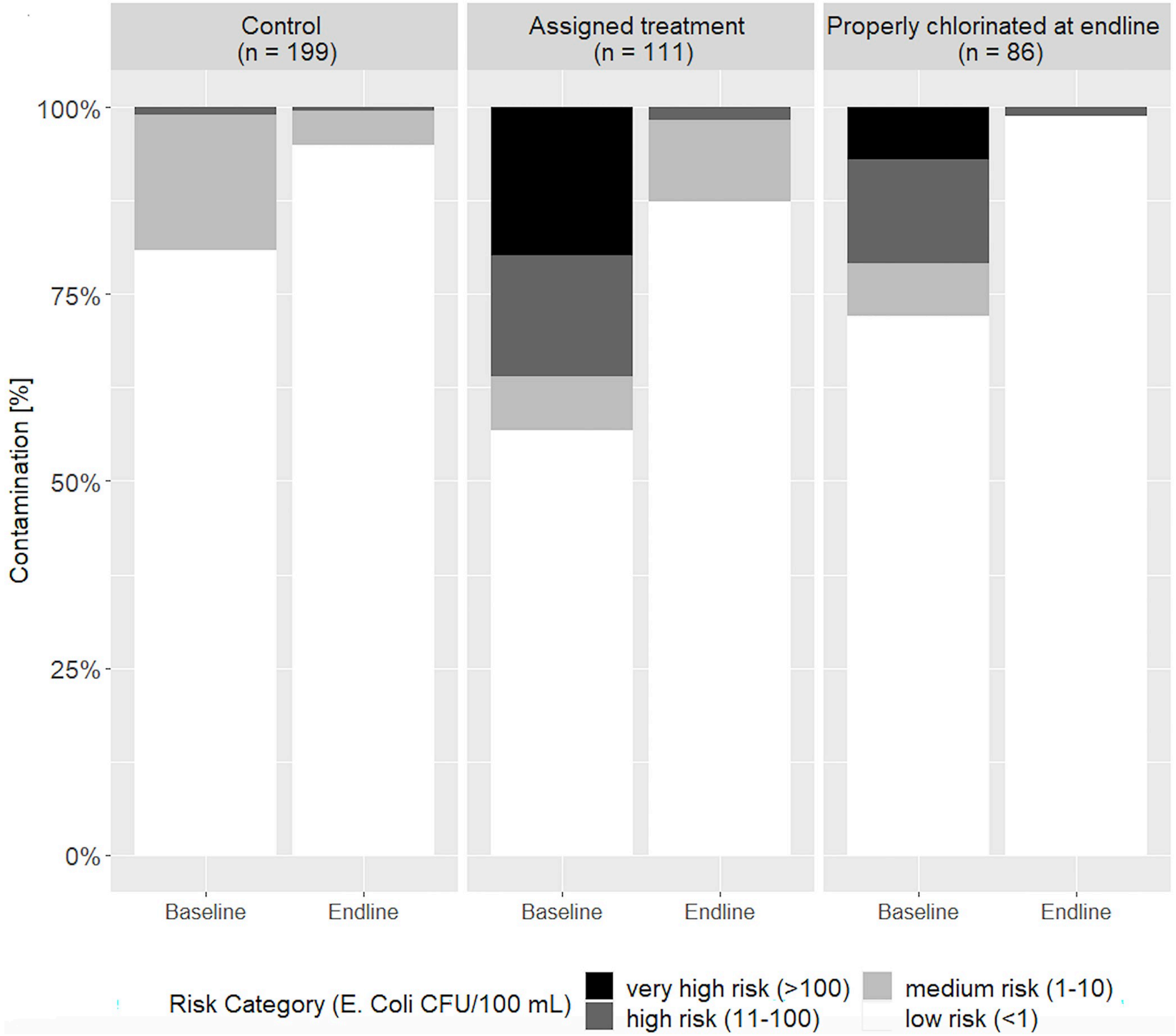

Fig 4. The risk categorisation [28] based on *E. coli* contamination for baseline and endline tap water samples from the control, treatment and the actively chlorinated WDS.

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chlorinated drinking water samples. More details are provided in S2 Table. The *E. coli* risk evaluation (S3 Fig) revealed there was a 4- and 9-point increase in the share of low risk household samples for control and actively chlorinated WDS samples, respectively. This corresponded to an overall rating of low risk for 92% of actively chlorinated WDS samples at endline.

Table 2. Difference-in-difference analysis of chlorination effects on *E. coli* levels in tap and household water samples in actively chlorinated WDS.

Sample	Observed log reduction	Observed % reduction	Log reduction attributable to chlorination	% reduction attributable to chlorination
Tap water	0.516	0.695	0.432	0.630
Household water	0.258	0.448	0.198	0.366

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The difference-in-difference analysis (Table 2) revealed that chlorination resulted in a decrease of 0.198 $\log_{10}$ CFU/100 mL for *E. coli*, equivalent to a 37% reduction in contamination (SE = 0.88, t = 2.225, p = 0.025) and accounting for 82% of the overall reduction in *E. coli*. This analysis could not attribute any significant change in total coliform concentrations in household drinking water samples to the intervention.

Regular monitoring visits. The A'Jín chlorinator was installed by Helvetas Guatemala in mid-October 2023 in WDS 3 and 9. We monitored FRC concentrations from the day the chlorinator was installed until mid-December (WDS 3) and mid-November (WDS 9) of 2023. In the follow-up monitoring visits (3 visits to WDS 3, 2 visits to WDS 9), we did not detect any FRC in the taps for either WDS. Similarly, the reservoir tank showed no detectable FRC for WDS 3, though we observed concentrations of 0.2 ppm and 0.09 ppm in the reservoir tank of WDS 9 during the last two visits. During monitoring visits for both WDS 3 and 9, concentrations were generally higher at the tank than the tap when FRC was detectable. Additionally, 97% of tap samples collected from WDS 3 and 9 had pH levels below 8, with a maximum of pH 8.1 and a mean of pH 7.1 (SD = 0.4). Only 51% of tap samples collected from these treatment WDS had detectable FRC concentrations (> 0.05 ppm), of which 17% had concentrations in the proper range of 0.2–0.5 ppm and 10% had concentrations above 0.5 ppm. From the samples with detectable FRC, 100% were free of *E. coli* and 78% were free of total coliforms. From the samples with no detectable FRC, 81% were free of *E. coli* and 55% free of total coliforms. See the S2 Fig and S5 Table for further details on the regular monitoring of taps and reservoir tanks. The water quality data collected in this study can be accessed at S3 Text.

Water committee and operator experiences with the A'Jín chlorinator

In the 4 WDS that were chlorinated with the A'Jín device, the responsibility of the chlorination was shared between all water board members, and they expressed technical comfort with the task. The operator estimated the proportion of users that were in favour of a chlorinated WDS to be "about half" in 2 systems, "less than half" in one WDS and "very few, it is mostly the water board that is convinced" in one WDS. Concerning FRC monitoring, 2 WDS collected measurements once per week and one WDS collected daily measurements; the fourth WDS indicated that it could not measure as it had not yet received the necessary measurement equipment from the NGO. The majority (3/4) indicated that they have had to adjust the dose in the past week, with 1 WDS increasing and 2 WDS decreasing the dosage. All WDS observed that the previous chlorine tablets were depleted before they refilled it.

Half of the WDS (2/4) received complaints from the users about the chlorine in the water. The complaints were a strong taste/smell of chlorine (2/2), discolouring of clothes when washing (1/2), concerns about causing hair loss (2/2), concerns about provoking cancer or other illnesses (1/2), and concerns about provoking sterility (1/2). Operators reported that users of these two WDS also indicated that chlorine is not needed, as they always drank their water without chlorine in the past. When asked if they think that the A'Jín chlorinator will still be actively used and functional one year from the endline visit, the operators of two WDS answered that they did not know, another answered with a maybe, and only one answered with a clear yes. The operators noted that the main challenges that might prevent continued use are the challenge of obtaining funds to buy the chlorine tablets (1/4), that the users do not want chlorination (2/4), and the work required to operate and maintain the chlorinator (1/4). One operator commented that they were not sufficiently convinced of the technical performance of the A'Jín chlorinator until this study.

As reported in the operator survey, interruptions of active chlorination that lasted longer than one week were explained by a lack of chlorine tablets for an extended period, a change in the water board committee and national holidays (specifically Christmas). Operators of the A'Jín also faced different technical problems that led to short-term interruptions in active chlorination. Because the A'Jín valves do not allow for precise adjustments of water flow, we observed that it was complicated to regulate the inlet and outlet valves such that the level of water inside the chlorinator stayed constant and at the correct level. We observed cases in which the chlorinator would both fill up completely such that water would spill through the upper lid or be completely empty and dried out. It was also common for the outlet valve to clog with calcium hypochlorite; as the tablet dissolved, it created a paste that blocked the outflow of water. During rainy season, the reservoir tank was often full, and the overflow pipe discharged excess water into a nearby stream. Further details on operators' experiences with the A'Jín chlorinator are reported in S7 Table.

Water users' perception and water management behaviour

Concerning household treatment, no strong change in practices was observed between baseline and endline for control and treatment WDS. There was a 5% increase in households that indicated boiling their water at endline, up from 80% and 81% (control and treatment WDS, respectively) at baseline. Other household treatments include chlorination (4%, 1%), use of eco-filter or other filter type (10%, 18%) and bottled water (3%, 2%) at baseline for control and treatment WDS, respectively. At endline, the number of households indicating treatment with chlorine at the household level increased by 5% for the treatment WDS and decreased by 3% for the control WDS. Concerning general satisfaction with their WDS, treated systems showed an increase in the share of satisfied households (from 84% to 98%) while control WDS remained relatively constant (98% to 99%). For treatment WDS, the percentage of households that perceived the taste as "good" decreased by 5%, though the percentage that reported being satisfied overall with the acceptability of their water's taste increased from 94% to 99% and with the water's smell from 93% to 95%. The ability to detect a taste and smell of "soil/dirt" decreased for both treatment and control households. In the treatment WDS, 4% detected a taste and 9% a smell of chlorine at endline compared to 0% at baseline, while no chlorine taste or smell was detected at endline in control WDS. More details are provided in S6 Table.

Discussion and conclusion

Passive in-line chlorination holds great potential for mitigating faecal contamination within WDS, potentially playing a crucial role in achieving universal access to safe water (SDG 6.1). The findings of this study provide valuable insights into the application of a low-cost, handmade A'Jín chlorinator in rural settings, as deployed by the RUK'U'X YA' program (Helvetas) in rural Guatemala. Our findings indicate that passive chlorination with the A'Jín device effectively reduced the faecal contamination of the tap water in three WDS in rural Guatemala. Initially, 28% of taps were found to be contaminated with *E. coli*, while at the end of the study, only 1% of taps tested positive for *E. coli* in WDS in which the A'Jín device was actively used for chlorination. A difference-in-difference analysis attributed a statistically significant log reduction of *E. coli* at taps to active use of the chlorinator, equivalent to a 63% reduction in faecal contamination. Similar observations of improved water quality at taps were made by Crider et al. in a study evaluating system-level chlorination in rural Nepal. However, the A'Jín device did not completely eliminate bacterial contamination and ensure the provision of safe tap water throughout the entire water distribution system. Among the actively chlorinated taps, 47% and 1% remained positive for total coliforms and *E. coli*, respectively, with mean contamination levels of 0.28 (SD = 0.81) and -0.29 (SD = 0.14) $\log_{10}$CFU/100 mL. This could be due to insufficient FRC concentrations or inadequate contact time prior to sampling.

The actively chlorinated WDS at endline exhibited an average FRC concentration of 0.25 ppm, with a dosing consistency (i.e., percent of collected samples meeting the target FRC minimum of 0.1 ppm mg/L) of 38% at the taps. This consistency is relatively low in comparison to other passive chlorination devices studied in different contexts, such as in Uganda [33], Liberia [34], Nepal [23], Honduras [35] and Bissau [36]. Other solid tablet chlorination devices, both handmade and industrial models, reported dosing consistencies ranging from 40–90% [16]. At endline, only 24% of taps achieved the targeted FRC concentration of >0.2 mg/L, as recommended by the WHO at the point of collection [12]. Lindmark et al. points out the importance of precision in chlorine dosing for an effective passive chlorination device. It should reliably dose within a range that maintains an acceptable taste and odour for end users while ensuring a sufficient FRC concentration to prevent recontamination during household handling and storage [37]. However, dosing problems could arise under conditions of acute bacterial contamination and/or an increase in natural organic matter within the WDS. Another explanation for inconsistent dosing is structural difficulties, such as long pipe mains [38], which could decrease the FRC concentrations at the tap level.

Passive, system level chlorination resulted in a higher coverage of safely managed water without requiring household-level behaviour change. Survey results indicate a high satisfaction with the WDS of users at endline; only a few users of chlorinated WDS reported perceiving a taste of chlorine. The longer-term acceptability of chlorination is uncertain due to the limited follow-up period of our study. Additionally, the decision to adopt chlorination in the treatment WDS was made by the users or the water committee, whereas these satisfaction levels might be more mixed if the chlorinator had been randomly assigned. It was observed that the A'Jín device had not been actively chlorinating one WDS for an extended period prior to the endline visit. Moreover, there was a lack of detectable FRC in this WDS. which could also affect the reported satisfaction levels.

Chlorination using the A'Jín resulted in a significant though relatively modest reduction in *E. coli* contamination of household drinking water as compared to the tap level analysis. A difference-in-difference analysis found a 0.20 $\log_{10}$ reduction in *E. coli* due to chlorination, equivalent to a 37% decrease in faecal contamination attributable to chlorination alone, pointing to the promise of the A'Jín device as a component of future WASH programs. However, the A'Jin did not completely eliminate contamination, and even infrequent exposure to faecal contamination can substantially increase health risks, as highlighted by Daly and Harris on the risk associated with even a single short-term exposure to highly microbially contaminated water [39]. In this study, FRC was detectable in 20% of household stored drinking water samples from chlorinated WDS, though the origins of these samples (bottled water, WDS, different system) and their treatment methods (boiling, filtration, UV, chemical disinfection) were not recorded. FRC concentrations in household stored drinking water samples were, on average, half that observed in tap water samples, which can be attributed to household water storage and handling practices [40]. Finally, while chlorine can effectively combat many pathogens responsible for waterborne illness, additional treatment steps may be required to remove chemical contaminants and protozoa that we were not able to measure.

Several difficulties were observed when using the A'Jín chlorinator. The imprecise valves and frequent clogging of the outlet valve made calibration and proper operation challenging, requiring frequent maintenance checks for effective chlorination. Feedback from one operator indicated that the high maintenance needs posed a significant challenge for future chlorination efforts in the community. Another operator expressed doubts regarding the technical performance of the device. Additionally, the generally distant location of the reservoir tanks from the village centre resulted in a high time burden placed on the water committee when operating and refilling the A'Jín device. In the opinion of one operator, remuneration would not alleviate this burden. Another challenge stemmed from managing chlorine dosing in the reservoir tank in rainy conditions. During the rainy season it was observed that the reservoir tanks were mostly full, with a high rate of water flow being discharged through an overflow pipe located near the inlet where the A'Jín was installed. Chlorinating at this stage was thus susceptible to large chlorine losses and inadequate mixing, especially because the outlet pipe to the distribution system was located at the bottom of the reservoir tank.

In this study in rural Guatemala, the water committees were observed to be very committed and well organised. This is important for ensuring the proper operation and maintenance of chlorination devices, as highlighted by Rayner et al. [41]. However, decision-making power regarding the WDS did not lie with the water committee but with the user assembly, which may hinder future efforts with passive chlorination in Guatemala, as it prevents chlorinators from being installed if the user assembly, a non-technical group who may be unfamiliar with water quality and treatment processes, does not agree. Illustrating the point with this study, only 5 WDS accepted to adopt chlorination, one of which never had it installed and another never actively used it because of the refusal of the user assembly. Previous studies have reported challenges with water users' controlling technical decisions about their water systems. In the present study site, we found that achieving public health aims for safe water services in Guatemala may require elected water committee members to assume the responsibility for and oversight of future chlorination interventions, rather than end users [42]. This aligns with the WHO guidelines for small supplies, which recommends a gradual move towards the professionalisation of small rural WDS through a stepwise, supported process [12].

The study has some limitations. First, the WDS receiving chlorination were self-assigned to the treatment group and thus were likely more motivated to improve their own water quality than if communities had been randomly assigned to groups. As compared to control communities, the communities opting into chlorination had a higher share of female heads of household (instead of male) and were mostly surrounded by agricultural land (instead of forest). Chlorinated WDS also had a higher number of connected households on average, with an operator receiving remuneration. These factors point to some of the fundamental differences between communities opting in and out of chlorination, which likely influenced our study results. Nonetheless, we consider the study design appropriate for an initial proof of concept assessment of the A'Jín device and have attempted to draw conclusions conservatively. Second, due to a short follow-up period, the observations represent a very early stage of implementation, such that some WDS were still in the calibration process of chlorinator implementation at the endline visit. We could thus not assess the sustained effectiveness and performance over time. Third, baseline and endline did not take place during the same season. While the influence of seasonal trends on the intervention's effect on water quality was accounted for by conducting a difference-in-difference analysis, uncertainties remain regarding the causal effect of chlorination on drinking water quality vis-a-vis other influencing factors (such as multiple source use) that may have been different across groups by season. Finally, we did not investigate any health outcomes, but focused only on *E. coli* as an indicator of pathogen risk, so cannot make direct conclusions on the health impact of the chlorination intervention. However, passive chlorination was found to improve the quality of tap and drinking water, contributing to reduced bacterial contamination and thus a lower risk of exposure to waterborne pathogens [43].

In conclusion, locally constructed passive chlorinators offer the advantages of being low cost, accessible and easily repaired using readily available materials. However, in the case of the A'Jín, disadvantages include frequent clogging and operational challenges. Limited time and economic resources in rural settings, where operators receive little or no remuneration for their efforts, impede the effective implementation of devices with high maintenance needs. While the original intention of passive chlorination was to prioritise user and operator convenience, the current design of the A'Jín device does not appear to effectively fulfil this purpose. To ensure future success, the A'Jín device would benefit from further prototype development, including rigorous testing and subsequent improvement phases, to focus on simplicity and ease of use and operation, supported by external technical assistance. This aligns with the trend of supported community supply in small rural communities [43]. For future research in the field, we suggest an assessment of the sustained effectiveness of promising passive chlorinator models over a longer period to gain a better understanding of their sustainability, of the operator dynamics and challenges, and of user perception. Moreover, we encourage the development of chlorinator models with simple operation and low maintenance needs that have undergone rigorous prototype development.

Supporting information

S1 Text. USEPA membrane filtration method 10029.
(PDF)

S2 Text. Sample size calculations, lab negative controls, duplicates, A'Jín chlorinator, regular monitoring.
(PDF)

S3 Text. Online repository containing the water quality data collected in this study.
(DOCX)

S1 Table. Duplicate statistics: Differences between the samples and their duplicates. [CFU/100 mL].
(PDF)

S2 Table. Household drinking water quality results for baseline and endline sampling.
(PDF)

S3 Table. Household characteristics at baseline visit.
(PDF)

S4 Table. Water distribution system baseline characteristics at baseline visit.
(PDF)

S5 Table. Regular monitoring water quality results before and after installation of the chlorinator for taps and reservoir tanks before and after installation of the chlorinator.
(PDF)

S6 Table. Tap water users' perceptions and satisfaction.
(PDF)

S7 Table. Operators' experience with the A'Jín chlorinator at water distribution systems with assigned chlorination.
(PDF)

S1 Fig. Precipitation events before and during baseline and endline visits.
(TIFF)

S2 Fig. pH of tap and drinking water at baseline, endline and during regular monitoring before and after the installation of the chlorinator.
(TIFF)

S3 Fig. Risk categorisation based on *E. coli* contamination for baseline and endline household drinking water samples for control, assigned treatment and properly chlorinated

WDS tap samples.
(TIFF)

S4 Fig. A'Jín construction.
(TIFF)

S5 Fig. A'Jín installation.
(TIFF)

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