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Booster Chlorination in Palestinian Schools: Field Investigation of Chlorination Dynamics in Central Hebron Directorate

Safa Sultan [1], Mohannad Nassar [1], Hassan Sawalha [1,*], Maher Jabari [1], Yaser Issa [2], Mohammad Abu Thrie [3], Gabriel Chevalier [4] and Maryna Peter [4]

[1] Center of Excellence in Water, Energy and Environment Research and Services, Mechanical Engineering Department, Palestine Polytechnic University, Wadi Al-Haria, Hebron P.O. Box 198, Palestine; safa.sultan@ppu.edu (S.S.); mjabari@ppu.edu (M.J.)
[2] Environmental Health Department, Ministry of Health, Hebron P.O. Box 16, Palestine
[3] Ministry of Education, Hebron P.O. Box 576, Palestine
[4] Institute for Ecopreneurship, School of Life Sciences FHNW, Hofackerstrasse 30, 4132 Muttenz, Switzerland
* Correspondence: hsawalha@ppu.edu

Abstract

Intermittent water supply is common in Palestine, prompting schools to rely on on-site water storage systems, including underground and roof tanks. Prolonged and uncontrolled water storage leads to quality degradation, especially with free residual chlorine (FRC) depletion. Hence, this poses health risks to students and staff. This pilot (field) study evaluated the effectiveness of booster chlorination under the current storage conditions to optimize and improve the existing chlorination process. Four schools were selected based on the type of water storage systems (two with underground tanks, two with roof tanks) and building age. Booster chlorination was applied at two chlorine doses (0.5 mg/L and 1 mg/L). FRC was monitored until levels dropped below 0.05 mg/L. Results show that the currently applied chlorine dose (0.5 mg/L) is insufficient to reach the minimum national FRC standard (0.2 mg/L) after 30 min. In contrast, a 1 mg/L chlorine dose is more effective in maintaining the minimum FRC concentration limit for a longer time. In addition, manual mixing is ineffective in large underground tanks, while it is effective in roof tanks. This study urges the need to revise the national chlorination guidelines and to adjust chlorination practices to ensure safe drinking water in schools.

Keywords: booster chlorination; chlorination procedure; free residual chlorine; chlorine dose; schools; underground storage tank; roof tanks

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Academic Editor: Maurizio Barbieri

Received: 20 September 2025
Revised: 9 November 2025
Accepted: 18 November 2025
Published: 28 November 2025

Citation: Sultan, S.; Nassar, M.; Sawalha, H.; Jabari, M.; Issa, Y.; Abu Thrie, M.; Chevalier, G.; Peter, M. Booster Chlorination in Palestinian Schools: Field Investigation of Chlorination Dynamics in Central Hebron Directorate. *Water* **2025**, *17*, 3405. https://doi.org/10.3390/w17233405

1. Introduction

Groundwater contributes to more than 90% of the drinking water supply in Palestine [1]. In general, groundwater quality in the West Bank meets World Health Organization (WHO) standards [2]. An evaluation of 29 groundwater aquifers revealed no fecal coliform contamination, despite the vulnerability of these karst aquifers to pollution [1]. Nevertheless, chlorination—using either gas or sodium hypochlorite—is routinely applied to all water supplies as a precautionary measure to avoid water quality depletion during distribution and storage [3]. Previous studies have shown that water quality deterioration often occurs within distribution networks, which can act as vehicles for pathogen transmission [4]. Microbial contamination has been detected in tap water even when treatment-plant water was free of contaminants, highlighting the importance of free residual chlorine (FRC) monitoring as an indicator of water safety and network integrity [5].

In the West Bank, over 94% of Palestinian residents are connected to piped water networks [6]. However, the supply is often intermittent, especially during summer, when water may be delivered only once every 50 days in some areas. Consequently, all households rely on water storage facilities, including roof and underground tanks with different capacities. This leads to prolonged stagnation and increased risk of chlorine decay. Booster chlorination at the consumer level is rarely practiced and typically implemented only after microbial contamination is detected, and for harvested rainwater, using a fixed chlorine dose of 0.5 mg/L [personal communication].

Previous local research has reported challenges in maintaining adequate chlorine levels under such circumstances. For example, detectable FRC was maintained along most of the distribution system in Nablus, North West Bank [3], but more than 40% of FRC measurements in Ramallah, Middle West Bank, were below the standard limits (0.2–0.8 mg/L) during the first 12 h after source water chlorination [3]. These deficiencies were largely attributed to the manual configuration of chlorination systems, the use of fixed chlorine dosing, and operational disruptions such as delays in refilling central chlorine tanks that may remain empty for hours or even days [2,7]. Similar challenges have been observed globally. In Mexico, for instance, despite the target FRC concentration being between 0.2 and 1.5 mg/L, coliforms and *E. coli* were detected in both household and public water supplies due to FRC depletion during distribution and storage [8].

Global research has focused on modeling and predicting chlorine decay in pipeline systems, exploring different factors like piping material, flow dynamics, and temperature [9,10]. However, considerably less attention has been directed toward chlorine behavior in intermittent supply systems with extended storage periods, particularly in institutional settings such as schools. These settings combine stagnancy, variable occupancy, and manual chlorination practices. These conditions are not well presented in existing predictive models or case studies.

Given the critical public health importance of maintaining safe chlorine levels, few studies have examined water quality in Palestinian schools. They identified significant FRC deficiencies associated with water storage issues. A recent study in Hebron found that 91% of school water samples showed inadequate FRC levels and over 20% of contained fecal coliforms [11]. Similar findings have been documented in Jenin, North West Bank [12]. These findings underscore the need to investigate how storage systems and operational practices affect chlorine decay and to identify appropriate, context-specific booster chlorination strategies.

Therefore, the recent study seeks to assess and optimize booster chlorination practices in Palestinian schools, with emphasis on systems characterized by intermittent supply and long storage periods. Different from other research that focused on continuous pipeline networks or theoretical chlorine prediction models, this work provides field-based experimental data and evaluates booster chlorination performance under real-world, institution-specific conditions.

Specifically, the study aimed to achieve the following:

1. To evaluate how the type of water storage system influences chlorine distribution and stability within the school's internal network.
2. To assess the impact of water storage duration on booster chlorination and determine the optimal chlorine doses needed to restore FRC levels in previously chlorinated water.
3. To develop recommendations for improving chlorination practices in schools, particularly considering extended water storage periods.

2. Materials and Methods

2.1. Overview of Water Management Systems in Schools

A general water management system in Palestinian schools is depicted in Figure 1. Schools are primarily supplied with water from the Palestinian Water Authority (PWA) or the national water company of Israel (Mekorot) through the municipal piped network (S1). Since water supply is intermittent, all schools rely on on-site water storage systems. These are typically a combination of underground storage tanks (ST1) and roof tanks (ST2). Meanwhile, some schools have roof tanks only. Roof tanks were made of steel, but are now being replaced by Polyethylene plastic tanks. The underground storage tanks are made of rocks or concrete and can be in the following shapes [13]:

- Pear-shaped tanks are excavated in rocky soil, with a narrow top that widens towards the bottom. They are common in older schools, but mostly sealed, as they are no longer allowed to be used for the storage of drinking water [14].
- Rectangular-shaped tanks are excavated in red soil—a fertile, iron-rich soil found in the Central Highlands of the West Bank—and constructed with reinforced concrete. These tanks are typically found in newer schools, with capacities reaching up to 500 m^3.

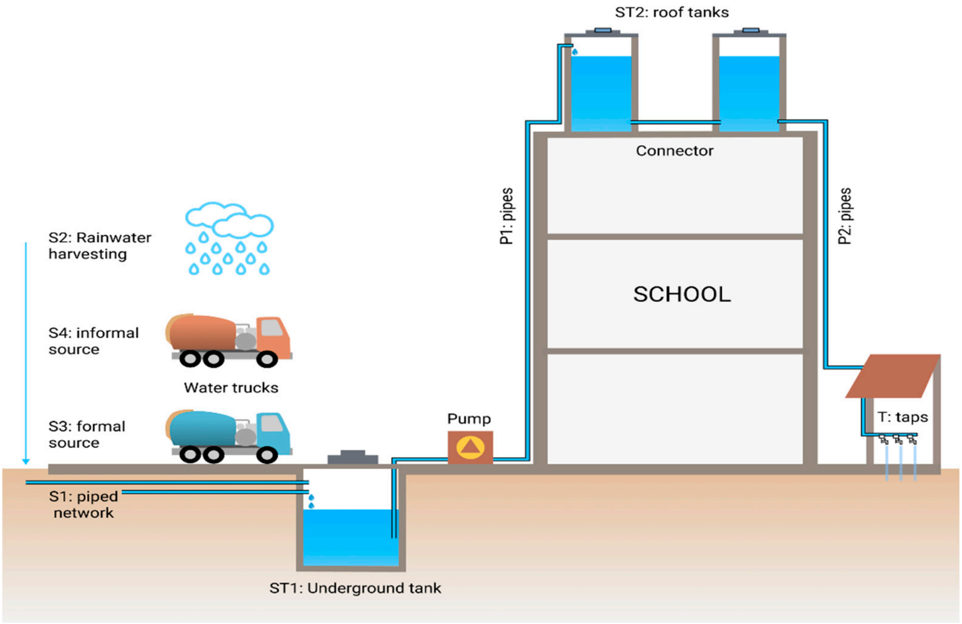

Figure 1. Schematic design of water management system in Palestinian schools © hands4health.

Received water is stored in underground tanks, often for prolonged durations, and subsequently pumped to roof tanks as required. Once the water in the roof tanks is consumed, the pumping system is automatically activated to refill the roof tanks.

During the summer months, some schools receive water once every 40–50 days via the municipal network due to frequent supply interruptions. Therefore, schools often suffer from water shortages and have to find alternative water sources, including the following:

- Harvested Rainwater (S2): Rainwater is typically collected from rooftops and stored in underground tanks. It is often mixed with chlorinated municipal water [11]. Based on the Ministry of Education (MoE) instructions, harvested water can be used only for non-drinking purposes such as irrigation or cleaning [14].
- Formal Sources (S3): Water provided by tankers operating under municipal supervision, filling their tanks from the municipal tankers' filling station, and providing chlorinated water.

- Informal Sources (S4): Water provided by tankers using uncontrolled water from their own springs that is often not chlorinated.

The majority of schools in Palestine are of medium age or recently constructed, featuring relatively modern infrastructure, including updated water storage and distribution systems. However, a considerable number of schools are housed in historic buildings that are over 100 years old. Many of these structures were originally built as castles or other traditional buildings and were not intended for use as educational facilities. To preserve their cultural and architectural heritage, and as a form of asserting presence in contested or symbolically important spaces, the MoE rented and repurposed these buildings for schooling. These older schools are typically small, equipped with outdated or dysfunctional underground water tanks, and have undergone partial modifications, such as the replacement of original piping systems with plastic alternatives.

The MoE monitors health-related aspects of schools, including water quality, through designated field coordinators. These coordinators conduct routine site visits to schools, during which they measure FRC levels. They also provide guidance on water sampling for microbiological testing when deemed necessary. In parallel, the MoE is developing an online chlorination monitoring system encompassing all schools in the West Bank. This tool offers real-time data, enabling the identification of schools with the highest susceptibility to water contamination. Additionally, it will support decision-making and enhance schools' health monitoring efforts.

The guideline 'water and hygiene in Palestinian schools', produced by the MoE, outlines that schools are required to clean their water storage systems before the start of each academic year. After cleaning, they are required to sample water for microbial testing in a certified laboratory. In addition, the Ministry of Health (MoH) collects random samples from schools on a weekly basis for quality evaluation and monitoring. Cleaning of tanks is carried out by hired personnel who scrub the interior surfaces of the tanks using regular cleaning detergents. However, chlorine is not used during the cleaning process. Furthermore, despite guidance instructing schools to chlorinate underground tank water after cleaning, chlorination is not applied to stored water. Based on field observations, while roof tanks are cleaned according to the instructions, cleaning and chlorination of underground tanks are usually reactive processes, conducted only after microbial contamination is detected.

2.2. Study Area

Hebron, which is located in the south of the West Bank, is considered the largest governorate. It includes 550 governmental schools serving 196,879 students across four local directorates: North Hebron, Hebron, South Hebron, and Yatta [15]. Table 1 shows the percentage distribution of schools in Hebron Governorate by the main source of water.

Table 1. Percentage distribution of schools in Hebron Governorate by the main source of water [15].

Directorate	**Main Source of Water %**		
	Piped Network	**Vended Water**	**Water Well (Underground Tank)**
North Hebron	96.3	1.5	2.2
Hebron	83.5	7.1	9.4
South Hebron	77.7	6.8	15
Yatta	52.4	21.4	26.2

The majority of schools receive water via a piped network from municipalities, where quality parameters, including chlorine levels, are monitored before distribution. Some schools primarily rely on vended water from both licensed and unlicensed sources. Other schools have underground tanks and are expected to rely on harvested rainwater. However, these statistics do not specify the percentage of schools that have underground tanks that are used only for storing municipal or vended water. Notably, in Yatta, half of the schools are not connected to the piped network. Instead, they rely more on vended and harvested rainwater.

2.3. Pilot Study-School Selection

For the purpose of evaluating the feasibility of the current chlorination process, four schools were selected to explore the process effectiveness. The school selection for this pilot study was based on the main source of water, the type of water storage system, and the age of the school. However, the selection had to be adjusted for two reasons. The Hebron Directorate of Education requested that the work be conducted during the summer break (mid-June to September) to avoid any potential risks for the students. In addition, the current political situation in Palestine significantly impacted mobility in the West Bank, even within the same governorate. Consequently, only four schools in accessible areas within Hebron city were chosen. The selection criteria, in addition to the initial ones, included having water in the storage tanks at the time of study and the availability of a school cleaner to assist during field visits and follow-up activities. Schools are anonymized and referred to as schools A, B, C, and D.

2.4. Field Survey and Water Management Systems Observation

A questionnaire was prepared to collect data on each school. Site visits were conducted to fill out the questionnaire, observe the water management systems, and estimate the available water volume. The main components of the water management systems of the selected schools are outlined in Table 2.

Table 2. Overview of the selected schools; system components are based on Figure 1.

School		**A**	**B**	**C**	**D**
Age		>100 years	<20 years	<20 years	>100 years
Number of students		126	400	330	200
System components		S1, S3, P1, ST2, P2, T	S1, ST1, P1, ST2, P2, T	S1, S3, ST1, P1, ST2, P2, T	S3, S1, P1, ST2, P2, T
Main water source		Piped network	Piped network	Piped network	Formal vendors
Main water storage tank		Roof tanks	Underground tank	Underground tank	Roof tanks
Available water volume in the main storage unit		9 m^3	120 m^3	50 m^3	9 m^3
Type of internal pipes		Plastic	Steel	Steel	Plastic
Last time cleaned	ST1	NA	10 years ago	September 2023	NA
	ST2	September 2023	August 2023	September 2023	September 2023

Note: NA: not applicable.

The volume of stored water was estimated using the following methods:

- For schools with roof tank systems: The calculation was based on the number of tanks, the observed water level, and the tank capacity (1.5 cubic meters per tank).
- For schools with underground tank systems: The water volume was estimated using the dimensions of the tank's base and the measured water depth. These tanks were rectangular in shape.

As Table 2 lists, two schools (B and C) have underground storage systems, while the other two schools (A and D) have only roof tanks. All schools cleaned their roof tanks between August and September 2023, approximately 10 months before chlorination experiments began. The cleaning procedure was the same in all schools without any use of chlorine during the process. However, the underground tank of school B had not been cleaned for 10 years.

2.5. Water Quality Assessment

Water quality was evaluated by collecting samples from taps and the main storage tanks (either roof or underground tanks) in the selected schools, one day prior to chlorination. The quality of source water supplying the schools was not tested due to the intermittent nature of the municipal supply and the fact that water had been stored in the schools' tanks for a period of time before experiments began. The collected samples were analyzed for a range of standard physicochemical and microbiological parameters that are commonly recommended for drinking water quality evaluation. The tested parameters are pH, temperature, total dissolved solids (TDSs), free residual chlorine (FRC), nitrates (NO_3), ammonium (NH_4), turbidity, total coliforms, and *Escherichia coli* (*E. coli*). The culture media used in this study also give an indication of the presence of *Pseudomonas*. Given the known role of *Pseudomonas* as a pathogen and its resistance to disinfection, it was considered as one of the tested parameters.

On-site measurements for pH, temperature, FRC, and turbidity were conducted using portable devices, while additional analyses were performed in the laboratory immediately after collection. A single sample was collected for field measurements, whereas triplicate samples were obtained from each sampling point for laboratory analysis. All tests were performed at room temperature (ambient air temperature).

The Milwaukee Model MW 102 pH/Temp meter (Milwakee instruments, Inc., Rocky Mount, NC, USA) was used to measure pH and temperature. Mobile water analysis compact photometer PF-12 Plus device (MACHERY-NAGEL GmbH & Co. KG, Düren, Germany) was used to measure FRC using free chlorine 2 visocolor ECO test kit (Ref. 931215) (MACHEREY-NAGEL GmbH & Co. KG, Düren, Germany). Turbidity was measured using a Portable turbidity meter (Model: TU-2016) (LUTRON ELECTRONIC Co., Inc., Coopersburg, PA, USA).

For the analyses of NO_3, NH_4, and TDS, samples were collected in 100 mL sterilized plastic bottles. The PF-12 Plus device was used for the measurements of NO_3 and NH_4 concentrations using the Colorimetric test kit VISOCOLOR ECO Nitrate (Ref. 931241), and the Colorimetric test kit VISOCOLOR ECO Ammonium 3 (Ref. 931208), respectively (MACHEREY-NAGEL GmbH & Co. KG, Düren, Germany). A Lutron YK-2005WA pH/ORP, DO, CD/TDS meter (LUTRON ELECTRONIC Co., Inc., Coopersburg, PA, USA) was used to test TDS levels.

For microbial analysis, samples were collected in sterilized plastic bottles containing sodium thiosulfate to neutralize chlorine. A 100 mL sample was filtered through a sterile membrane (47 mm, 0.45 μm porosity) (Sartorius Stedim Biotech, Yauco, PR, USA) and placed on a compact dry 'Nissui' EC plate for coliforms, *E. coli*, and *Pseudomonas aeruginosa* (Nissui Pharmaceutical Co., Ltd., Tokyo, Japan). Each dry plate was moisturized with 1 mL of the sample. After incubation at 35 ± 2 °C for 24 ± 2 h, bacterial growth on the plates was recorded: red colonies for coliforms, blue colonies for *E. coli*, and milky white colonies indicate the presence of *Pseudomonas*. Microbial tests were repeated 30 min after chlorination for schools that showed positive results for microbial detection.

2.6. Chlorination Procedure

Booster chlorination experiments were conducted in two stages:

- Stage 1: The national chlorine dose recommended by the Ministry of Health, which is 0.5 mg/L, was applied in schools A and B. This phase took place from the end of June until August.
- Stage 2: A doubled chlorine dose (1 mg/L) was applied in schools C and D. This dose was selected to keep FRC concentration at the tap level below 0.8 mg/L, as recommended by the MoE, and avoid affecting water palatability. This phase was implemented from mid-July to early November.

Chlorination followed the local standard procedure: HTH granules (calcium hypochlorite, 66%) were sourced from the environmental health department at Hebron Directorate of Health. The granules were dissolved in a 5 L plastic bucket using a wooden stirrer for mixing. The solution is left to stand for 10 min, then poured into the water and mixed thoroughly.

For underground systems, the chlorine solution was poured into the underground tank. The bucket was attached to a rod to be used for mixing. In the roof tanks, the chlorine solution was evenly distributed across all the tanks and mixed using the wooden stirrer. After chlorination, the water was left to stand for 24 h.

The required amount of HTH granules was calculated using the following equation [16]:

$$\text{weight of chlorine powder (g)} = \frac{\text{target FRC } \left(\frac{\text{mg}}{\text{l}}\right) * \text{water volume (L)} * 1000}{\text{active chlorine concentration}} \tag{1}$$

2.7. FRC Monitoring

During the follow-up phase, FRC concentration, pH, and temperature were recorded for water samples taken directly from both the chlorinated units and from taps. For roof tank systems, two tanks were randomly selected to represent the chlorinated system, and the average FRC value was recorded. Due to operational constraints, a single measurement was taken per sampling event.

The first FRC reading was taken 30 min after chlorination, directly from the chlorinated units. The second reading was taken after 24 h.

The Monitoring schedule was as follows:

- Three days per week during the first week;
- Two days per week during the second week;
- Once a week for the remainder of the follow-up period.

The total number of samples varied among schools, as sampling was based on the detection of residual chlorine. Measurements were stopped once the FRC value dropped below <0.05 mg/L, the lowest detectable limit of the device used.

Water consumption patterns were not explicitly incorporated into the study due to the limited occupancy of schools during the summer break. Most schools had minimal water use during the study period. However, one school (School C) hosted a summer camp and carried out cleaning activities during the experiment, leading to intermittent water consumption.

3. Results and Discussion

3.1. Water Quality

The results of water quality testing for samples collected from the selected schools are presented in Table 3 along with the standard limits set by the Palestinian Standard Institution (PSI). The findings indicate that pH, TDS, nitrate, and ammonium concentrations were all within the PSI standard limits across all samples. Most samples, however, exhibited turbidity levels slightly above the preferred limit (0.5 NTU), especially school A and the underground tank of school C. The elevated turbidity in the latter may be attributed to a white film layer observed on the water surface, likely resulting from sediment accumulation or microbial activity.

Table 3. Results of water quality testing from the selected schools.

School	**A**		**B**		**C**		**D**		**Standard Limit (PSI)** [17]
Sample Source	**T**	**ST2**	**T**	**ST1**	**T**	**ST1**	**T**	**ST2**	
Parameter									
pH	8	8.02	8.04	8.06	8.18	8.03	-	8.12	6.5–9.5
Temperature (Degree Celsius)	32.1	31.8	26.7	26	29.3	27.6	-	29.8	-
FRC (mg/L)	0	0	0	0	0	0	-	0	0.2–0.8
Turbidity (NTU)	0.9	0.88	0.52	0.44	0.48	1.13	-	0.64	Acceptable by consumers (best < 0.5)
TDS (mg/L) mean ± SD (n = 3)	388 ± 4.5	388 ± 4.2	392 ± 2.6	387 ± 3	410 ± 2.6	413 ± 2.9	-	467 ± 3.6	Acceptable by consumers (best 100 < TDS < 600 and not more than 1000)
NO_3 (mg/L) mean ± SD (n = 3)	16.3 ± 0.45	16.2 ± 0.43	12.9 ± 0.35	12.5 ± 0.39	17 ± 0.43	16.9 ± 0.39	-	16.1 ± 0.46	50
NH_4 (mg/L) mean ± SD (n = 3)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	-	<0.1	0.5
Total coliforms (CFU/100 mL) mean ± SD (n = 3)	0	0	0	0	0	0	-	0	9 ± 2.6
E. coli (CFU/100 mL) mean ± SD (n = 3)	0	0	0	0	0	0	-	0	0
Pseudomonas (CFU/100 mL) mean ± SD (n = 3)	18 ± 3.6	3 ± 1.5	0	0	70 ± 4.3	100 ± 3.6	-	0	0

FRC was undetectable in all schools, both in tap water and storage tank samples. This was likely due to a combination of factors, including initially low chlorine concentrations in the supplied water, prolonged storage time, and possible chlorine demand caused by organic or microbial matter in the system. Although fecal coliforms and *E. coli* were absent in all samples, indicators for the presence of *Pseudomonas aeruginosa* were observed for all schools except school B, which depends solely on piped municipal water. *Pseudomonas* species are commonly found in soil, water, and plants, and can enter water storage systems through environmental contamination. Once established, they form biofilms that persist over a long time and might even become resistant to chlorine at low concentrations. A significant correlation between total coliforms and *Pseudomonas* presence has been reported in the literature [18], often linked to inefficient water treatment, inadequate cleaning of storage systems, and formation of biofilms in plastic pipelines, especially PE-HD and PVC-U plastic types [19,20].

Despite School B not having cleaned its underground tank for approximately ten years, it showed no microbial contamination. This may be attributed to the sole dependence on chlorinated municipal water supplied via a piped network and the consistently covered underground tank, which together help minimize contamination risk. However, this setup does not prevent the depletion of FRC during storage and distribution within the school's premises, potentially leaving the system vulnerable to microbial regrowth.

Microbial testing repeated after booster chlorination demonstrated that both 0.5 and 1 ppm chlorine doses effectively eliminated *Pseudomonas* within 30 min. Previous studies have documented *Pseudomonas* resistance to chlorine disinfection, especially at low chlorine levels [18,21,22]. However, WHO states that maintaining FRC levels at 0.5 mg/L for a minimum of 30 min, in addition to regular cleaning of water storage and distribution systems, can be effective in mitigating its presence [16].

The uniformity of physicochemical parameters across all schools confirms that they received water originating from a consistent municipal source of stable quality. The absence of chlorine residuals in all samples further indicates complete chlorine decay during storage. Therefore, variations observed later in chlorination performance are more reasonably attributed to site-specific factors such as storage duration, tank conditions, and operational practices rather than variations in source water quality.

3.2. Booster Chlorination and FRC Monitoring

In the first stage of the experiment, the locally recommended chlorine dose of 0.5 mg/L was applied in schools A and B. In school A, chlorine was added directly to the roof tanks (ST2) that contained relatively old water stored for over a month. The tanks were about three-quarters full of stagnant water due to the summer break during which no water consumption occurred. The night before chlorination, a fresh supply from the municipality had been added, filling the tanks completely and resulting in a mixture of old and new water in the tanks.

As shown in Figure 2, the FRC measured after 30 min of chlorination was 0.16 mg/L and showed no significant change after 24 h. This suggests that chlorine demand within the tanks was almost satisfied within the first 30 min. FRC was first detected at the tap on the sixth day after chlorination. This delay was due to several reasons: (1) minimal water use during the school break, with taps opened only for FRC sampling; (2) the chlorine demand of the internal piping system (P2), which had to be satisfied before chlorine could reach the tap (T), after which the chlorine concentration at the tap matched that in the roof tanks, confirming that the entire system had been thoroughly disinfected; and (3) scheduling delays due to the weekend following chlorination.

Chlorine persisted in the stored water for 12 days under static conditions without any water consumption. FRC levels remained below the standard limits throughout the monitoring period, indicating that the applied chlorine dose of 0.5 mg/L was insufficient to maintain the minimum required FRC of 0.2 mg/L under the given conditions.

In school B, the same chlorine dose of 0.5 mg/L was applied to the underground tank (ST1) that was full of old stored water. The last water delivery had occurred two weeks prior to chlorination, and older water had been in the tank before this delivery. As depicted in Figure 3, despite dosing at 0.5 mg/L, FRC levels were 2.8 mg/L after 30 min, and decreased slightly to 2.5 mg/L after 24 h. When water was pumped to the roof tanks, FRC dropped to 0.47 mg/L, likely due to the turbulence caused by pumping, which facilitated partial mixing of chlorine, but was insufficient for uniform distribution throughout the system. FRC continued to decline gradually, reaching 0.17 mg/L by day 28 when water was pumped again, dropping FRC further to 0.07 mg/L. The lower threshold of 0.2 mg/L was reached after approximately 13 days, and FRC ultimately disappeared after 36 days.

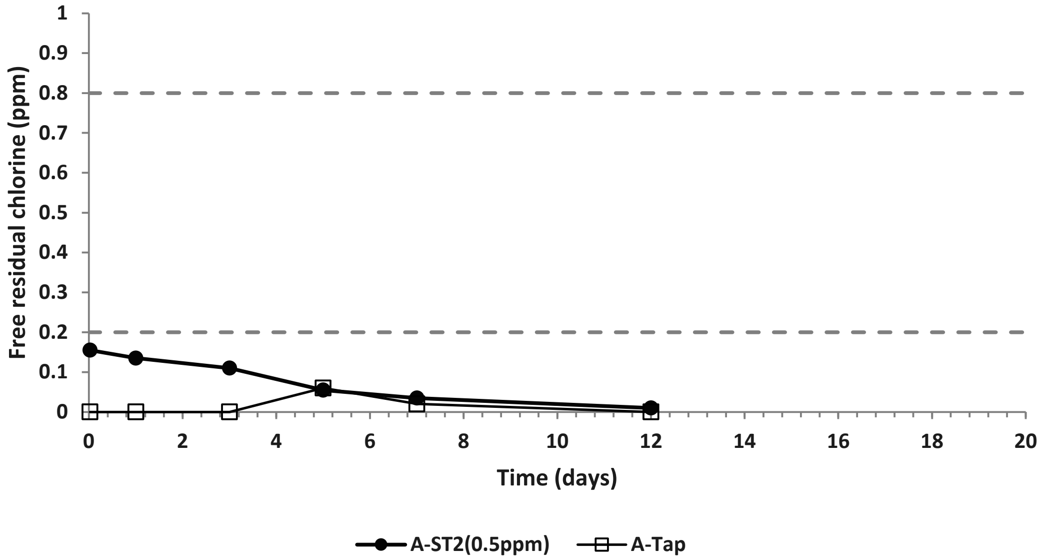

Figure 2. FRC decay dynamics in school A with roof tanks at a chlorine dose of 0.5 mg/L. FRC monitoring in roof tanks and taps started after 30 min after chlorination until the reading dropped below 0.05 mg. Dashed lines indicate the PSI standard limit for FRC.

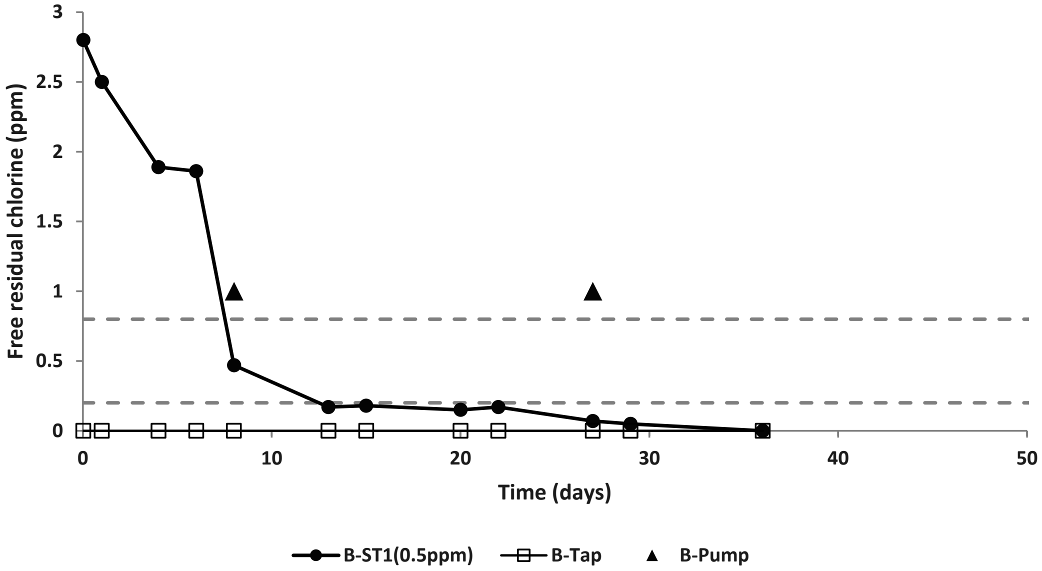

Figure 3. FRC decay dynamics in school B with an underground tank at a chlorine dose of 0.5 mg/L. FRC monitoring in the underground tank and taps started after 30 min of chlorination until the reading dropped below 0.05 mg. Dashed lines indicate the PSI standard limit for FRC.

Notably, FRC remained undetectable in the roof tanks and at the tap. This is likely due to (1) the long distance between the underground and the roof tanks (P1), which allowed chlorine to be consumed in the pipes, especially since the whole storage system had never been disinfected, and (2) the presence of old water in the roof tanks (ST2) with no FRC. When newly chlorinated water arrived, any remaining chlorine that had not been consumed in the pipes was used to partially satisfy the chlorine demand of the old water. However, it was insufficient to maintain a detectable FRC at the tap. This highlights that even if adequate FRC exists in the main storage tank, it may not always reach the tap.

In the second stage of the experiment, a doubled chlorine dose (1 mg/L) was applied at schools C and D, following the same procedures as in the first two schools. FRC decay dynamics in school C are presented in Figure 4. After 30 min of chlorination of the underground tank, FRC was 2.7 mg/L and dropped to 1.68 mg/L after 24 h. Similar to school B, the improper manual mixing method led to uneven chlorine distribution and higher initial FRC readings in the tank.

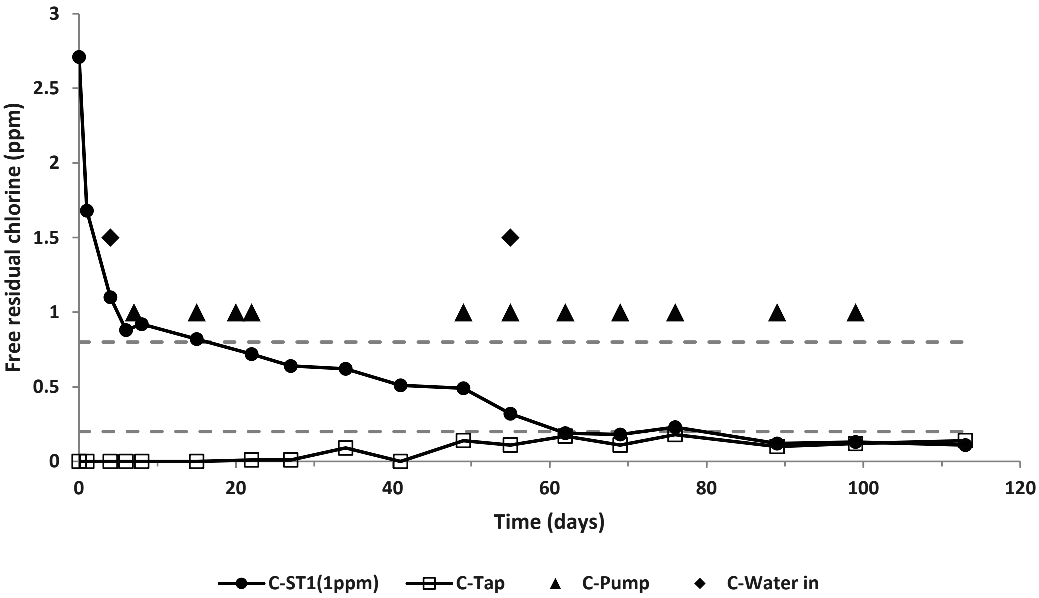

Figure 4. FRC decay dynamics in school C with an underground tank at a chlorine dose of 1 mg/L. FRC monitoring in the underground tank and taps started after 30 min of chlorination until water depletion in the underground tank. Dashed lines indicate the PSI standard limit for FRC.

The underground tank was half full at the time of chlorination and was refilled with municipal water via the water network after four days. Although the FRC of the incoming water was not measured, it was assumed to be chlorinated. The mixing of new and old water likely influenced FRC dynamics. By day 7, FRC had dropped to 0.88 mg/L, suggesting that chlorine demand had not been fully satisfied yet, possibly due to ongoing mixing turbulence.

Although the school was on summer break during the experiment, a summer camp was hosted after two weeks of chlorination, making this a special case in this study. Water consumption resumed partially during the camp compared to regular school days, with multiple pumping events. Following the camp, cleaning activities commenced in preparation for the new academic year. Increased water use and pipe flushing helped to disinfect the system (P1, ST2, P2, T) and renew water inside roof tanks, resulting in detectable FRC at the tap. By day 60, FRC at the tap matched the underground tank concentration, indicating that the system had been effectively disinfected.

On day 56, the school received a new municipal water with an FRC of 0.18 mg/L, which was mixed with the chlorinated water that had an FRC of 0.32 mg/L on that day. A week later, the mixed FRC stabilized at 0.19 mg/L and remained consistent for approximately two weeks.

The experiment was stopped on day 113 with FRC still above 0.05 mg/L due to water depletion in the underground tank. The upper PSI standard limit for FRC (0.8 mg/L) was reached after 16 days, and the lower limit (0.2 mg/L) was achieved after 60 days.

School D, despite being connected to the piped network, its high elevation and lack of a water pump meant that it primarily relied on formally vended water as an alternative supply. Chlorine was added to the roof tanks (ST2) that were full of a mixture of old water from a former vendor (S3) and some new water from the municipal piped network (S1) received a few days before chlorination.

After 30 min of chlorination, FRC was 0.52 mg/L and slightly decreased to 0.48 mg/L after 24 h (Figure 5). FRC was first detected at the tap on the second day. Initially, the

FRC of tap water was lower than that in the roof tanks, implying chlorine consumption along the pipes (P2). Over time, as the piping system was disinfected, FRC at the taps increased. Subsequently, FRC at the tap gradually declined in parallel with the roof tanks. Some tap measurements were higher than those in roof tanks, likely due to water mixing from multiple tanks connected together and supplying the same taps. Additionally, the regular opening of the tank cap during sampling could affect the available chlorine in the sampling tank.

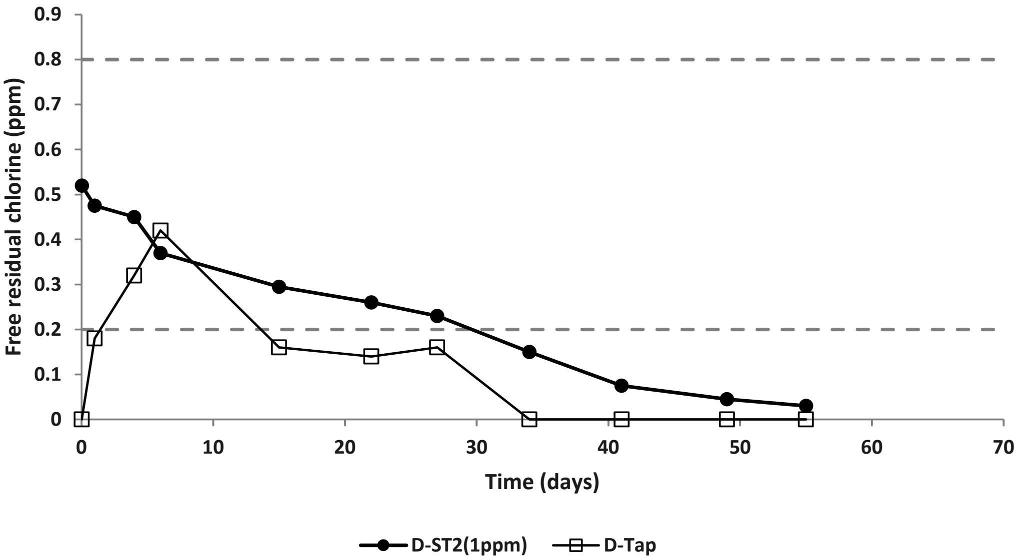

Figure 5. FRC decay dynamics in school D with roof tanks at a chlorine dose of 0.5 mg/L. FRC monitoring in roof tanks and taps started after 30 min of chlorination until the reading dropped below 0.05 mg/L. Dashed lines indicate the PSI standard limit for FRC.

Despite targeting an FRC of 1 mg/L, the upper limit of the PSI standard was not reached. Nevertheless, FRC remained above 0.2 mg/L for more than 30 days and declined below 0.05 mg/L after 55 days.

Figure 6 compares the results of booster chlorination in schools A and D, both of which rely on roof tank systems. In these systems, water mixing occurred rapidly and thoroughly, allowing an effective removal of contaminants and satisfaction of chlorine demand within the first hours of chlorination. Subsequently, a breakthrough of chlorine at the tap level occurred within a few days. Notably, doubling the chlorine dose (to 1 mg/L) significantly extended the presence of FRC, maintaining levels within the standard limits for a longer period compared to the 0.5 mg/L dose. With the lower dose, FRC fell below the minimum recommended limit of 0.2 mg/L almost immediately, which is inconsistent with the guideline of keeping at least 0.2 mg/L FRC at the point of consumption for stored water [23].

Figure 7 depicts chlorine decay dynamics in schools B and C, both using underground storage systems. Despite being dosed differently, both exhibited similar initial FRC concentration after 30 min of chlorination. This is likely due to poor mixing in the underground tanks that left chlorine concentrated near the water surface. Chlorine behavior thereafter varied due to differences in water consumption, introduction of new water, and the applied chlorine dose. Water consumption requires pumping, which generates turbulence, improving mixing and increasing chlorine contact with water, which also aids in disinfecting piping systems and allows better detection at taps. In School C, for example, daily water pumping after about 50 days of chlorination resulted in the FRC at the tap matching that of the underground tank.

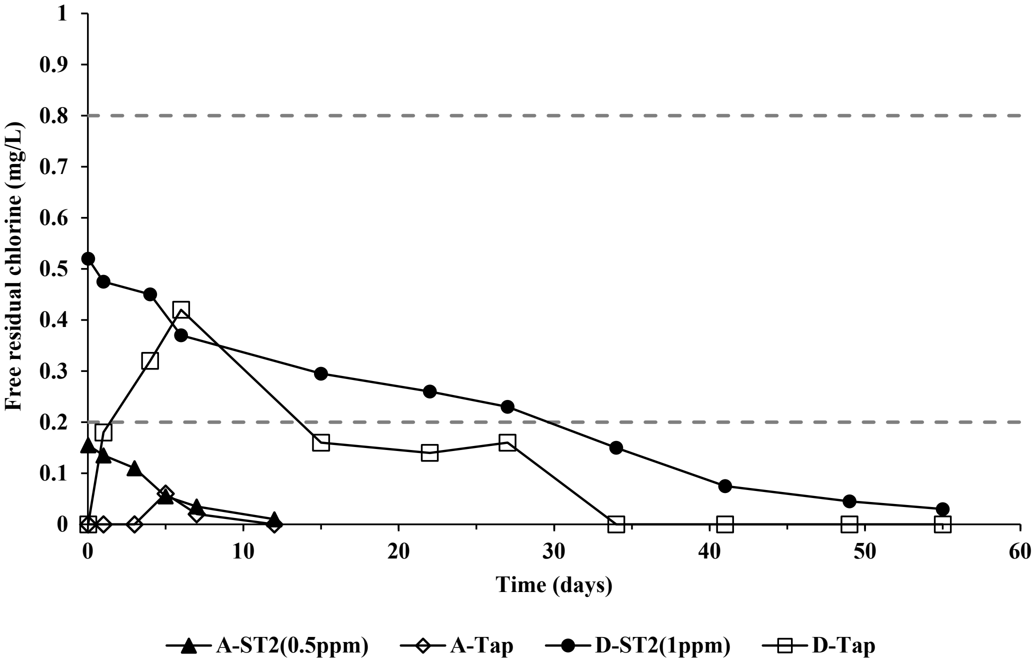

Figure 6. FRC decay dynamics in schools with roof tanks at different chlorine doses. A 0.5 mg/L dose was used in school A, and a 1 mg/L dose was used in school D. FRC monitoring in roof tanks and taps started after 30 min of chlorination until the reading dropped below 0.05 mg/L. Dashed lines indicate the PSI standard limit for FRC.

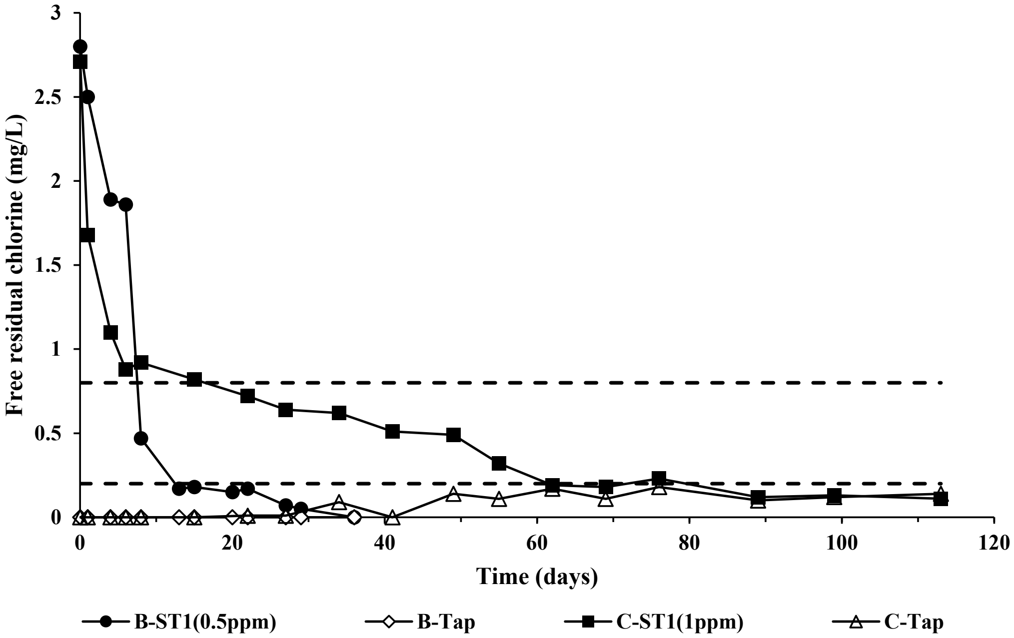

Figure 7. FRC decay dynamics in schools with underground storage tanks at different chlorine doses. A 0.5 mg/L dose is used in school B, and a 1 mg/L dose is used in school C. FRC monitoring in underground tanks and taps started after 30 min of chlorination and lasted until the reading dropped below 0.05 mg/L. Dashed lines indicate the PSI standard limit for FRC.

Old stored water generally has a higher chlorine demand than freshly chlorinated water [16]. In school B, pumping water to the roof tanks caused a sharp drop in FRC levels. The lack of water consumption prevented system refreshing, leaving the taps without detectable chlorine and indicating incomplete disinfection of the piping system (P2). In contrast, school C achieved entire system disinfection, aided by water consumption during the summer camp and by the introduction of new chlorinated water twice during the follow-up period, further extending chlorine persistence. Notably, doubling the chlorine dose (to 1 mg/L) maintained FRC in the system roughly three times longer.

To quantitatively describe the observed chlorine decay patterns, the kinetics of FRC decay seem to follow first-order kinetics in all studied schools. The natural logarithm of FRC, Ln(CA), decreased linearly with time, confirming that the FRC decay process could be adequately described by first-order kinetics, as illustrated in Figure 8. The figure shows a strong agreement between the experimental values and the fitted model, despite some scatter in the data points, indicating that first-order kinetics reasonably represent the chlorine decay process under the tested conditions.

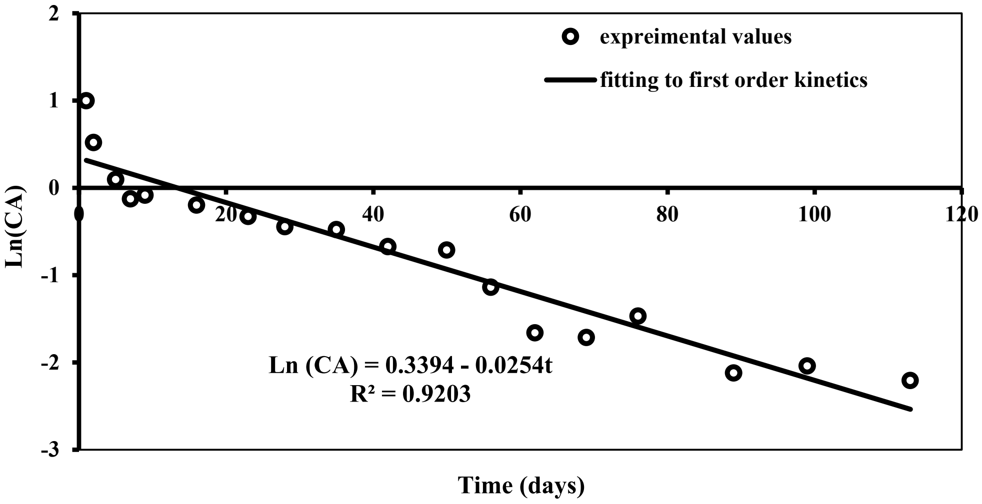

Figure 8. Fitting of the FRC decay dynamics to a first-order kinetics model. Experimental data were obtained from Figure 4 for school C, with an underground tank at a chlorine dose of 1 mg/L.

3.3. Considerations for Chlorine Dosing in School Water Systems

Finding a chlorine dose that meets the water's chlorine demand, maintains sufficient residuals during storage, and remains within standard limits without affecting user acceptance is challenging [24,25]. In the current study, a chlorine dose of 1 mg/L has been found sufficient to maintain FRC levels in stored water. Higher dosages were avoided for the following reasons. First, increased chlorine can adversely affect water palatability, potentially leading schools to reject chlorination or switch to alternative water sources for drinking. Second, local acceptance of higher chlorine doses is limited due to concerns about allergic reactions and complaints from students, parents, or school staff if chlorine is noticeably present. In such cases, ensuring water quality through proper covering of storage tanks, regular cleaning, and reliance on trusted water sources is preferred over increasing chlorine doses [24]. Finally, the formation of disinfection by-products should also be considered, especially since school water is often pre-chlorinated.

3.4. Operational Challenges and Recommendations for Booster Chlorination in Schools

Regular application of booster chlorination in schools presents significant operational challenges, due to time and labor costs, along with the lack of trained personnel. School cleaners, often tasked with chlorination, may not be fully equipped to perform this responsibility, especially in cases where gender norms or other constraints limit participation. Furthermore, the MoE field coordinator is not always available to oversee the process. These challenges are likely to extend to other regions where point-of-use chlorination is required, which may result in neglected water treatment [26].

To address these issues, training sessions should be organized to build the capacity of personnel responsible for cleaning and chlorination, ensuring proper and consistent execution of these tasks.

Chlorination of roof tanks, where chlorine solution must be manually added to each tank, is particularly impractical. The MoE could consider providing central storage tanks for schools that rely solely on roof tanks. Chlorination could then be applied at the central tank before water is distributed to individual roof tanks, reducing labor and improving residual chlorine levels.

Another operational challenge is the inconsistent supply of chlorine from the Ministry of Health, which adds financial strain. Increasing chlorine dosage at the source could help maintain residual chlorine levels in school water.

Complementary proactive measures, such as ensuring reliable water sources, regular cleaning, and maintenance, would collectively enhance FRC levels and overall water quality.

A related study evaluated batch chlorination in underground tanks using liquid chlorine [27]. A ‘two-bucket method’ was employed, where chlorine solution was prepared in two separate 20 L buckets instead of one to distribute a lower chlorine concentration over a larger area, improving dosing uniformity despite the absence of a mechanical mixing device. Adapting this approach to the Palestinian context could improve mixing, particularly if combined with the local manual mixing techniques. Alternatively, redesigning the pump connection to allow flow reversal during operation could also enhance mixing.

4. Conclusions

This study examined the effectiveness of booster chlorination in schools with different water storage systems under the specific Palestinian conditions of intermittent supply and extended storage periods. The results demonstrated that the commonly applied chlorine dose of 0.5 mg/L was insufficient to maintain the minimum required FRC of 0.2 mg/L, particularly in systems with old or stagnant water. Increasing the dose to 1 mg/L significantly improved chlorine persistence and maintained FRC within the recommended limits for a longer duration, particularly in underground tanks.

However, chlorination effectiveness was influenced by several additional factors beyond dose. The age and quality of stored water, mixing technique, design of storage and distribution systems, and the level of water consumption all played critical roles in FRC stability.

The manual mixing method commonly used was found to be inadequate in underground tanks, leading to uneven chlorine distribution and delayed detection at the tap.

Regular water consumption and the introduction of fresh, pre-chlorinated municipal water improved chlorine circulation, promoting effective disinfection of the entire system.

Limited technical capacity, irregular chlorination, and lack of trained personnel reduce the consistency of water treatment in schools. Addressing these challenges requires capacity building, better mixing and dosing practices, and the potential use of centralized storage systems where feasible.

Overall, effective booster chlorination in schools should consider operational context and infrastructure characteristics. Proper dosing, adequate mixing, regular cleaning, and improved management practices can collectively ensure stable FRC levels, enhancing drinking water safety in educational settings.

5. Recommendations

The following recommendations are made for improving chlorination practices in school water systems:

- Increase chlorine dose to at least 1 mg/L to ensure effective disinfection throughout the system and prolonged FRC presence.
- Improve mixing methods (e.g., through water circulation and/or preparing chlorine solution) in underground storage tanks to ensure uniform chlorine distribution.
- Clean water storage systems of schools before the start of each academic semester and apply booster chlorination immediately after water refilling.
- Periodically disinfect piping systems by allowing water to circulate through the entire water system one hour after chlorination; this step helps to disinfect the internal piping, particularly in long or plastic pipe systems.
- Apply chlorination to stored water in the underground tanks when summer break starts to safeguard water quality during extended storage periods.
- Conduct further studies to include (1) additional schools, especially those relying on untrusted water sources, to develop special recommendations for these cases; and (2) FRC monitoring during regular school operation when occupancy and consumption are at typical levels.

Author Contributions: Conceptualization, S.S., M.J., H.S., Y.I. and M.A.T.; methodology, S.S., M.J. and H.S.; investigation, S.S. and M.N.; data curation, S.S. and M.N.; writing—original draft preparation, S.S.; writing—review and editing, S.S., H.S., M.J., G.C. and M.P. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to thank the Swiss Agency for Development and Cooperation for partially funding this study through the hands4health project (7F-l 0345.03.01).

Data Availability Statement: The original data presented in this study are included in the article (figures and tables). Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FRC	Free residual chlorine
WHO	World Health Organization
PWA	Palestinian Water Authority
S	Water source
ST	Storage tank
P	Pipes
MoE	Ministry of Education
MoH	Ministry of Health
TDS	Total dissolved solids
NO_3	Nitrates
NH_4	Ammonium
E. coli	*Escherichia coli*
PSI	Palestine Standards Institution
NTU	Nephelometric turbidity unit
CFU	Colony Forming Unit

References

1. Mahmoud, N.; Zayed, O.; Petrusevski, B. Groundwater quality of drinking water wells in the West Bank, Palestine. *Water* **2022**, *14*, 377. [CrossRef]
2. Hamdan, M.M. Chlorination Efficiency and Chlorine Decay in Water Distribution Systems in Palestine: The Case of Kufor Malek. Master's Thesis, Berzeit University, West Bank, Palestine, 2012.

3. Haddad, M.; Mcneil, L.; Omar, N. Model for predicting disinfection by-product (DBP) formation and occurrence in intermittent water supply systems: Palestine as a case study. *Arab. J. Sci. Eng.* **2014**, *39*, 5883–5893. [CrossRef]
4. Lee, E.J.; Schwab, K.J. Deficiencies in drinking water distribution systems in developing countries. *J. Water Health* **2005**, *3*, 109–127. [CrossRef] [PubMed]
5. Goyal, R.V.; Patel, H.M. Analysis of residual chlorine in simple drinking water distribution system with intermittent water supply. *Appl. Water Sci.* **2015**, *5*, 311–319. [CrossRef]
6. Annual Report on the Performance of Water Sector Regulatory Counci. Available online: https://www.wsrc.ps/public/uploads/Publication/1710152520614149.pdf (accessed on 15 January 2025).
7. Zidan, N.; Maree, M.; Samhan, S. An IoT based monitoring and controlling system for water chlorination treatment. In Proceedings of the 2nd International Conference on Future Networks and Distributed Systems, Association for Computing Machinery, Amman, Jordan, 26 June 2018.
8. Nielsen, A.M.; Garcia, L.A.T.; Silva, K.J.S.; Sabogal-Paz, L.P.; Hincapié, M.M.; Montoya, L.J.; Galeano, L.; Galdos-Balzategui, A.; Reygadas, F.; Herrera, C.; et al. Chlorination for low-cost household water disinfection–A critical review and status in three Latin American countries. *Int. J. Hyg. Environ. Health* **2022**, *244*, 114004. [CrossRef] [PubMed]
9. Zin, N.N.; Kazama, S.; Takizawa, S. Network Model Analysis of Residual Chlorine to Reduce Disinfection Byproducts in Water Supply Systems in Yangon City, Myanmar. *Water* **2021**, *13*, 2921. [CrossRef]
10. Costa, J.; Mesquita, E.; Ferreira, F.; Figueiredo, D.; Rosa, M.J.; Viegas, R.M.C. Modeling Chlorine Decay in Reclaimed Water Distribution Systems—A Lisbon Area Case Study. *Sustainability* **2023**, *15*, 16211. [CrossRef]
11. Sultan, S.; Sawalha, H.; Issa, Y.; Nassar, M.; Qaimari, H.; Abu Thrie, M.; Jabari, M. Characterization and evaluation of physio-chemical and microbiological water quality parameters in Palestinian schools: A case study from Central Hebron Directorate. Euro-Mediterr. *J. Environ. Integr.* **2024**, *10*, 877–886. [CrossRef]
12. Khalil, R.; Mahmoud, N. Assessment of drinking water quality at public schools at Jenin Directorate of Education, Palestine. *Desalin. Water Treat.* **2022**, *275*, 196–206. [CrossRef]
13. Khatib, I.A. *Guidelines for Rainwater Harvesting at Household Level*; Berzeit University: West Bank, Palestine, 2016. Available online: http://hdl.handle.net/20.500.11889/4386 (accessed on 10 November 2024).
14. Hmeidat, A.; Sahal, R.; Nazzal, R.; Al-Khatib, S. Scientific preparation and review. In *Water and Hygiene in Palestinian Schools*; Shreidah, R., Ed.; Ministry of Education: Ramallah, Palestine, 2022; pp. 10–13.
15. Education Statistics Yearbook 2023/2024. Available online: https://www.moe.edu.ps/uploads/%D8%A7%D9%84%D9%83%D8%AA%D8%A7%D8%A8%20%D8%A7%D9%84%D8%A7%D9%95%D8%AD%D8%B5%D8%A7%D9%8A%D9%94%D9%8A%20%D8%A7%D9%84%D8%AA%D8%B1%D8%A8%D9%88%D9%8A%20%D8%A7%D9%84%D8%B3%D9%86%D9%88%D9%8A.pdf (accessed on 11 March 2025).
16. World Health Organization. *Principles and Practices of Drinking-Water Chlorination: A Guide to Strengthening Chlorination Practices in Small-to Medium Sized Water Supplies*; World Health Organization, Regional Office for South-East Asia: Geneva, Switzerland, 2017.
17. Palestine Standards Institution. Mandatory Technical Instructions 108-2023 for Water intended for Human Consumption. 2023. Available online: https://www.psi.pna.ps/en/mandotaryInstruction?category=1&page=1 (accessed on 10 November 2024).
18. Anversa, L.; Stancari, R.C.A.; Garbelotti, M.; Ruiz, L.S.; Pereira, V.B.R.; Nascentes, G.A.N.; Dantas, S.T.A.; Rall, V.L.M. Pseudomonas aeruginosa in public water supply. *Water Pract. Technol.* **2019**, *14*, 732–737. [CrossRef]
19. Erdei-Tombor, P.; Kiskó, G.; Taczman-Brückner, A. Biofilm formation in water distribution systems. *Processes* **2024**, *12*, 280. [CrossRef]
20. Li, X.; Gu, N.; Huang, T.Y.; Zhong, F.; Peng, G. Pseudomonas aeruginosa: A typical biofilm forming pathogen and an emerging but underestimated pathogen in food processing. *Front. Microbiol.* **2023**, *13*, 1114199. [CrossRef] [PubMed]
21. Gholipour, S.; Nikaeen, M.; Mehdipour, M.; Mohammadi, F.; Rabbani, D. Occurrence of chlorine-resistant Pseudomonas aeruginosa in hospital water systems: Threat of waterborne infections for patients. *Antimicrob. Resist. Infect Control* **2024**, *13*, 111. [CrossRef] [PubMed]
22. Mao, G.; Song, Y.; Bartlam, M.; Wang, Y. Long-term effects of residual chlorine on Pseudomonas aeruginosa in simulated drinking water fed with low AOC medium. *Front. Microbiol.* **2018**, *9*, 879. [CrossRef] [PubMed]
23. OXFAM WASH. Chlorination in Emergencies. Available online: https://www.oxfamwash.org/chlorination-in-emergencies/ (accessed on 22 January 2025).
24. Ali, S.I.; Ali, S.S.; Fesselet, J.F. Evidence-based chlorination targets for household water safety in humanitarian settings: Recommendations from a multi-site study in refugee camps in South Sudan, Jordan, and Rwanda. *Water Res.* **2021**, *189*, 116642. [CrossRef] [PubMed]
25. Wilhelm, N.; Kaufmann, A.; Blanton, E.; Lantagne, D. Sodium hypochlorite dosage for household and emergency water treatment: Updated recommendations. *J. Water Health* **2018**, *16*, 112–125. [CrossRef] [PubMed]

26. Crider, Y.S.; Tsuchiya, M.; Mukundwa, M.; Ray, I.; Pickering, A.J. Adoption of point-of-use chlorination for household drinking water treatment: A systematic review. *Environ. Health Perspect.* **2023**, *131*, 016001. [CrossRef] [PubMed]
27. Voth-Gaeddert, L.E.; Lemley, M.; Willford, I.; Brathwaite, K.; Momberg, D.; Schranck, A.; Libbey, S. Evaluating a large-scale batch chlorination method for household cistern water treatment in the US Virgin Islands. *J. Environ. Eng.* **2022**, *148*, 04022063. [CrossRef]