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Impact of Gravity-Driven Membrane Filtration Water Treatment Systems on a Rural School in Indonesia

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Abstract: Improving access to safe drinking water in developing countries is still a challenge and Gravity-Driven Membrane (GDM) filtration systems may be a sustainable solution. Two rural schools in West Java Indonesia were studied, one as a control site and another having an installed GDM system. Chemical and microbiological water quality data were collected for an initial 3-month period at the GDM site and a final sampling at the study's conclusion (6 months) at both sites. After the initial 3-month period, health surveys were conducted with students self-reporting incidences of diarrhea for 3 months at both school sites. An analysis of the chemical parameters indicated that both schools had good water quality. An average 2-log reduction of fecal indicator bacteria at the GDM site was observed, with the control site having numbers that exceeded the upper detection limits (>3.38 log CFU/100 mL). Student diarrhea incidence at the GDM site declined from 0.077 at the survey onset to 0.052 at the latter half of the survey period, while the control site had a diarrhea incidence of 0.077 throughout. The results indicate that GDM technology can serve as a practical water filtration technology, improving access to safe drinking water for rural populations.

Keywords: water quality; filtration; water treatment; GDM; child health; rural schools

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1. Introduction

A long-term challenge to global health goals has been the access to improved drinking water for low- and lower-middle-income countries (LMIC) to reduce the incidence of diarrheal diseases. Some progress has been made as the estimated global deaths of children younger than 5 years old declined in 2011 to 6.9 million, from 12 million deaths in 1990 [1]. However, attaining a sustainable development goal of 25 or fewer deaths per 1000 live births is still a challenge, where 2018 reports indicate approximately 5.3 million deaths in children under 5 years old occurred globally [1]. While these mortality figures account for poor nutrition, respiratory diseases, and lack of adequate health care, exposure to infectious diseases due to poor drinking water, sanitation, and hygiene behaviors (WASH) also contribute to these mortality rates, and 2016 estimates from global exposure data indicated that 5.3% of all deaths for children under the age of 5 were attributed to diarrheal disease [2]. Some regions within Western and Central Africa and Central and Southern Asia have populations that are especially susceptible, and among these countries, diarrhea accounts for 8% of mortality for young children [1,3].

Of the 276.4 million people in Indonesia, 43.4% live in rural areas [4]. While most Indonesian water facilities are considered medium to low contamination risks, a 2019 survey of over 6000 facilities indicated that 3.97% had fecal bacteria contamination issues [4]. For young children under the age of five, diarrheal disease is still a public health concern, with prevalence estimated nationwide at 11% [3]. A survey of 2626 children diagnosed with diarrhea indicated that, while viruses were identified commonly as causative agents for infection, approximately 10% were attributed to bacterial infections [3]. For older children at ages between 5 and 14 years, the annual incidence of diarrhea in South and Southeast Asian populations ranged from 15.4% to 91.7%, with a median of 67.5% [5]. Indonesia has made strides in access to improved drinking water (over 75% coverage); yet, there is still a large disparity in child diarrheal mortality, with some regions within the country being 4 times greater than the country average [6,7].

A possible technology to offer improved drinking water can be through Gravity-Driven Membrane (GDM) filtration. The advantages of these systems are that they utilize hydrostatic pressure to achieve filtration through hollow fiber units that require no power and need little maintenance for long-term operation [8,9]. The filtration efficacy performance after several months can be high, with reports of bacteria removal ranging from 2 to 4 logs, and in some cases greater than a 3.9-log for protozoa [10,11].

The evaluation of water quality for fecal contamination is commonly reliant on the detection and enumeration of fecal indicator organisms based on cultivation methods that typically detect *Escherichia coli* or fecal enterococci [12,13]. Their detection in water can be indicative of the presence of pathogens, and some specific strains of *E. coli*, such as O157:H7, can be associated with outbreaks [14,15]. Cultivation and enumeration techniques to detect fecal indicators in water commonly utilize selective media, and one such method uses a commercially available media, Colilert (IDEXX Laboratories), which can be modified using the Quantity-Tray (QT) system to allow for quantification [16].

A 2022 systematic review of water, sanitation, and hygiene (WASH) research in Indonesia concluded that a limited number of WASH studies were conducted in schools and that more were needed to effectively determine what programs would be effective in these settings [17]. The purpose of this study was to determine the impact a GDM water treatment system would have on the water quality and student health for Indonesian children in a rural school, and, further, to establish if this technology could demonstrate the efficacy of its filtration performance after several months.

2. Materials and Methods

Two schools located in Cisolok, Sukabumi District, West Java, Indonesia (SMP PGRI 1 Cisolok and SMP Naringgul) were selected for this study (Figure 1). This region was chosen due to its appropriate ties to local government officials in order to support our field study efforts and the presence of facilities partnered with Korean project members who were required for the rapid laboratory processing of water samples for microbiological analysis (within 8–10 h). The selected schools utilized natural runoff as water sources, and the student demographics and student populations were approximately similar to each other. One school would have a Gravity-Driven Membrane (GDM) water treatment system installed while another would serve as a control site.

Installation using a Gravity-Driven Membrane (GDM) water treatment system and water quality monitoring was undertaken at SMP Naringgul, and a two-tank system was installed using the existing, runoff-fed water source for the school (GDM site). Each 1000 L tank was installed sequentially. The first tank was utilized as a simple sedimentation tank, with runoff flow feeding into a final filtration tank serving as a point-of-use drinking water source (Figure 2).

School	Latitude	Longitude	Elevation
SMP PGRI 1 Cisolok	−6.89591368	106.46266476	420 m
SMP Naringgul	−6.91217659	106.46901683	302 m

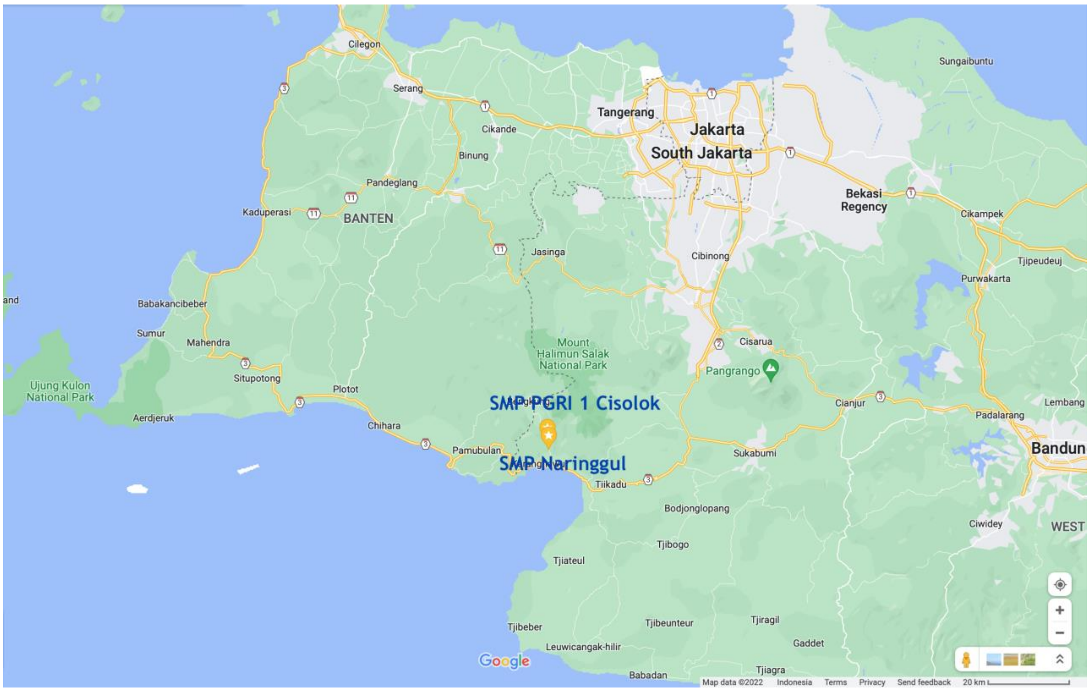

Figure 1. Location of School Sites.

(**a**) (**b**)

Figure 2. Gravity-Driven Membrane (GDM) System at SMP Naringgul. (**a**) GDM filter unit; (**b**) layout of primary sedimentation (topmost) and filtration tanks (foreground).

The outflow of the final filtration water storage tank had a series of six 0.35 m^2 GDM filters made of polyvinylidene fluoride (PVDF) with a total filtration area of 4.2 m^2. PVDF has good chemical resistance, is of relative sturdy strength, and demonstrates excellent aging resistance [18]. The membrane filters had a pore size of 20–40 nm and were obtained from a commercial source (Amogreentech, Gimpo, Korea), and the filtered water obtained from the tank would serve as a point-of-use water source for the student population. For the school site with no water filtration system (control site), water was obtained from the system previously installed at the school, which was fed from a natural runoff source. For both school sites, the existing water sources were not used for drinking water and were only used for sanitation and washing of hands by the students and staff.

Initial water sampling events were conducted monthly over a 3-month period at the GDM site and once after 6 months from GDM installation. The post-6-month sampling event at the GDM site also included water samples collected at the control site school. For the GDM site, water was collected after filtration and also from unfiltered water within the storage tank, while the control site also had water collected from a storage tank. Microbial analysis was done using cultural methods. Approximately 100 mL of water was collected in duplicate in sterile polypropylene bottles aseptically. Samples were maintained at approximately 8°C on blue ice until processing in the laboratory (within 8 h). For the total coliform, *E. coli*, and fecal enterococci, 100 mL portions of each water sample were analyzed, and MPN enumeration was conducted using Enterolert and Colilert-18 media (IDEXX, Westbrook, ME, USA). Incubation conditions for each analysis followed the manufacturers' recommendations, and the interpretation and enumeration were done after 18 h of incubation. Presumptive counts from the MPN chamber wells expressing typical reactions (Enterolert and Colilert-18, IDEXX, USA) were normalized to log counts per 100 mL.

Simple physical parameters of the water samples were collected on-site, while more intensive chemical analyses had volumes of 500 mL or 1 L collected for further laboratory analysis. For the laboratory analysis of metal constituents, 500 mL samples were filtered using filter paper and preserved using 65% nitric acid, while 1 L water samples were used for the analysis of other parameters. Water testing methods for physical and chemical parameters along with analysis methods utilized are listed in Table 1.

Initial surveys of student demographics were conducted throughout various Cisolok schools prior to the installation of the GDM water treatment system. This was done to obtain general information on the various student populations within the region to better establish the potential impacts of water treatment systems for schools. Further, a brief survey of water consumption and sources of water (both at home and at school) for the students was conducted for the two selected schools. For water consumed at schools, students were asked to report if the water they drank was obtained from their home (Home), bottled water supplied by the school (Bottled), bottled water they bought themselves (Bought), or water supplied from the local water source at the school (Supplied by School). Additionally, one final survey on water consumption patterns was done at each school to determine if there were any changes in consumption practices for the students at the conclusion of the study.

After sufficient initial water testing was completed from the installed GDM system (a 3-month period), water characteristic parameters were below Indonesian Ministry of Health limits, indicating that it was safe for consumption and that the students were allowed to freely drink water from the GDM treatment system under the supervision of school staff. Student health surveys were conducted at each of the two schools to obtain self-reported incidences of diarrhea. Students were surveyed to recall if they experienced symptoms of three or more bowel movements of watery stools for a period of 24 h or more. The health surveys were conducted twice a week for three months, asking the student to recall any incidents from up to three to four days prior. This information and the survey frequency were deemed appropriate based on published studies [19,20]. Incidence rates were determined as a simple proportion of students recalling incidents of diarrhea over the total number of students surveyed. Survey data over a 3-month period were split into two sets, an initial set (from the onset of the health surveys until the 6- week mark) and a late set (from the 7th week to the final survey event). This was done to facilitate analysis to determine any potential changes in the incidence rates of diarrhea for the student groups.

Table 1. Physical and chemical parameters for water analysis.

Parameter	Unit	Maximum Limit *	Analysis Method
Temperature	°C	-	Thermometer
pH	-	-	Portable pH meter/pH indicator universal
Total dissolved solids (TDS)	mg/L	500	APHA 23rd Ed. 2540 C
Free chlorine (Cl_2)	mg/L	5	HACH (based on APHA 23rd Ed. 4500-Cl D)
Zinc (Zn)	mg/L	3	Flame atomic absorption spectrometry (FAAS) (SNI 6989.7:2009)
Manganese (Mn)	mg/L	0.4	Flame atomic absorption spectrometry (FAAS) (SNI 6989.5:2009)
Iron (Fe)	mg/L	0.3	Flame atomic absorption spectrometry (FAAS) (SNI 6989.4:2009)
Copper (Cu)	mg/L	2	Flame atomic absorption spectrometry (FAAS) (SNI 6989.6:2009)
Total chromium (Cr)	mg/L	0.05	Flame atomic absorption spectrometry (FAAS) (SNI 6989.17:2009)
Nickel (Ni)	mg/L	0.07	Flame atomic absorption spectrometry (FAAS) (SNI 6989.18:2009)
Cadmium (Cd)	mg/L	0.003	Graphite furnace atomic absorption spectrometry (GFAAS)
Lead (Pb)	mg/L	0.01	Graphite furnace atomic absorption spectrometry (GFAAS)
Barium (Ba)	mg/L	0.7	Graphite furnace atomic absorption spectrometry (GFAAS)
Arsenic (As)	mg/L	0.01	Atomic absorption spectrometry (AAS) (based on APHA 23rd Ed. 3114 C)
Selenium (Se)	mg/L	0.01	Atomic absorption spectrometry (AAS) (based on APHA 23rd Ed. 3114 C)
Mercury (Hg)	mg/L	0.001	Cold Vapor Atomic Absorption Spectroscopy (CVAAS) (based on SNI 6989.78:2011)
Sodium (Na)	mg/L	200	Atomic Absorption Spectroscopy (AAS) (based on APHA 23rd Ed. 3110)
Cyanide (CN^-)	mg/L	0.07	APHA 23rd Ed. 4500 E
Total ammonia nitrogen (NH_3-N)	mg/L	1.5	Titration
Nitrate (NO^{3-})	mg/L	50	APHA 23rd Ed. 4500-NO_3 E
Nitrite (NO^{2-})	mg/L	3	APHA 23rd Ed. 4500-NO_2 B
Fluoride (F^-)	mg/L	1.5	Spectrophotometry with SPADNS (based on SNI 06-6989.29-2005)
Chloride (Cl^-)	mg/L	250	Argentometric Mohr (based on SNI 6989.19:2009)
Sulfate ($SO_4{}^{2-}$)	mg/L	250	Turbidimetry (based on SNI 6989.20:2009)
Odor/aroma	-	odorless	Organoleptic
Color	TCU	15	Spectrophotometry (based on SNI 6989.80:2011)
Taste	-	tasteless	Organoleptic
Methylene blue active substances (MBAS)	mg/L	0.05	APHA 23rd Ed.5540 C
Hardness as $CaCO_3$	mg $CaCO_3$/L	500	Titrimetry (based on SNI 06-6989.12-2004)
Turbidity	NTU	5	Nephelometer (based on SNI 06-6989.25-2005)
$KMnO_4$	mg/L	10	Titrimetry (based on SNI 06-6989.22-2004)

* Maximum limit permitted by Indonesian Ministry of Health.

All statistical analyses were done with R, an open-source statistic program (the R Foundation). Survey questionnaires for the students were evaluated and approved by members of the Research Ethical Committee of the Deputy of Social Sciences and Humanities, the Indonesian Institute of Sciences (Sub-komisiKlirensEtik IPSK-LIPI) prior to their implementation.

3. Results

3.1. Student Demographic and Water Usage Surveys

Among the 21 schools surveyed over the 2-year period, there were a total of 3631 students with the gender totals of the students being 1913 male and 1718 female. The average per class was 91.1 and 82.5, male and female students, respectively. SMP Naringgul had, on average, 118 students over the 2-year period, including an average of 70 boys and 64 girls per school, while SMP PGRI 1 Cisolok had an average of 316 students, with 165 boys and 151 girls averaged among the student population. An analysis using the Fisher exact test showed no significant difference in the proportion of male and female students for the selected schools compared to the proportion of the average students for all of the surveyed schools within the region (a p value of 0.997 and 0.996 for SMP Naringgul and SMP PGRI 1 Cisolok, respectively). The results for student water consumption habits and sources are provided in Tables 2 and 3. For both schools, bottled water was the most common source of water consumed at home, followed by well water, and a fair number of students from SMP PGRI 1 Cisolok (43 responses) used surface water as a source at home. Most households employed some manner to treat water consumed at home, with boiling being the most common means.

The volume of water consumed increased in the 500 mLto 1 L category and was nearly 2-fold for the GDM school at the conclusion of the study (72% from 32.8%, initially) compared to little change in the control site from the pre- and post-surveys (52% and 60%, respectively). This was coupled with a large increase in the school being the source of water for students at the GDM site, shifting from 22.2% in the pre-survey to 98% in the post-study survey. In contrast, either bottled or bought water was still the most common source of water consumed by students at the control site, both at the beginning and conclusion of the study.

Table 2. Home water sources and treatment for students.

School Site	Where Do You Get Your Water from Home?							
	Ground/Well Water							
	Well Depth Less than 10 m	Well Depth More than 10 m	Piped Water from Village	Rainwater	Bottled Water (No Brand)	Bottled Water (AQUA)	Surface Water (River, Stream, Pond)	Other
GDM	18	14	6	0	69	14	17	1
Control	75	37	6	1	97	35	43	0
School Site	Do You Treat the Water You Drink?			How Do You Treat the Water You Drink?				
	Yes	No	No Response	No Treatment	Boil	Chlorine/Chemical	No Response	
GDM	107	30	0	27	107	3	0	
Control	226	52	16	51	222	5	16	

Table 3. School water consumption and sources for students.

School Site	Sampling Period	How Much Water Do You Drink at School Each Day?			Where Does the Water You Drink at School Come from?			
		Less than 500 mL	500 mL to 1 L	More than 1 L	Bottled	Bought	Supplied by School	Home
GDM	Initial (n = 137)	76 (55.5%)	45 (32.8%)	16 (11.7%)	16 (11.9%)	49 (36.3%)	30 (22.2%)	40 (29.6%)
	Final (n = 150)	23 (15.3%)	108 (72%)	19 (12.7%)	0	3 (2%)	147 (98%)	0
Control	Initial (n = 279)	111 (39.8%)	145 (52%)	23 (8.2%)	93 (33.3%)	125 (44.8%)	2 (0.72%)	59 (21.2%)
	Final (n = 200)	59 (29.5%)	120 (60%)	21 (10.5%)	38 (19%)	132 (66%)	20 (10%)	10 (5%)

Values presented as frequencies (with percentage in parenthesis).

3.2. Water Quality Monitoring

Mean bacterial counts after the GDM installation decreased by approximately 1.5 to 2 log MPN/100 mL. This reduction also resulted in exceedingly low counts of *E. coli* and fecal enterococci (Table 4), with *E. coli* counts below the maximum permitted limits by the Indonesian Ministry of Health standards (0 MPN/100 mL). At the 6-month period, there was an increase in the total coliforms, which was above the Indonesian Ministry of Health limits of 0 MPN/100 mL. In contrast, the control site had counts of the total coliforms, *E. coli*, and fecal enterococci that exceeded the upper detection limit of 3.38 log MPN/100 mL. The averages for the chemical and physical water parameters are provided in Table 5. To establish means for some of the parameters where values of the replicates fell below the detection limit thresholds, those values were reported as half the detection limit for that parameter [21]. For the parameters tested, both sites fell within the Indonesian Ministry of Health guidelines except for two parameters at the control site. Mean values at the control site for turbidity and $KMnO_4$ were 39.5 NTU and 11.05 mL/L, respectively, exceeding the recommended limits (5 NTU and 10 mg/L).

Table 4. Mean microbial counts for GDM site.

Organism	GDM Treatment	Overall	9 Week	6 Month
Total Coliforms	Unfiltered	2.98 (n = 3)	2.77 (n = 2)	3.38 (n = 1)
	Filtered	0.68 (n = 5)	0 (n = 3)	1.69 (n = 2)
E. coli	Unfiltered	1.64 (n = 3)	1.45 (n = 2)	2.01 (n = 1)
	Filtered	0 (n = 5)	0 (n = 3)	0 (n = 2)
Fecal Enterococci	Unfiltered	1.74 (n = 3)	1.45 (n = 2)	2.61 (n = 1)
	Filtered	0 (n = 6)	0 (n = 5)	0 (n = 1)

Values are Mean Log MPN/100 mL.

Table 5. Mean values of chemical parameters.

Site	Temp (°C)	pH	Total Dissolved Solids	Free Chlorine	Zn	Mn	Fe	Cu	Total Cr	Ni	Cd	Pb
GDM	26.63	7.5	245.6	<0/1	0.033	<0.3	0.169	0.014	<0.05	<0.07	<0.0001	<0.001
No GDM	27	7.5	226	<0.1	0.008	0.026	0.119	0.014	0.034	<0.07	<0.0001	<0.001
Control	28	6.6	60	<0.1	0.01	<0.03	<0.1	0.04	<0.05	<0.07	<0.0001	<0.001

Site	Ba	As	Se	Hg	Na	Cyanide	Total Ammonia	Nitrate	Nitrite	Fluoride
GDM	<0.004	<0.002	<0.004	<0.001	11.4	<0.004	<0.3	2.29	0.005	0.048
No GDM	<0.004	<0.002	<0.004	<0.001	11.5	<0.004	<0.3	4.34	0.007	0.06
Control	<0.004	<0.002	<0.004	<0.001	8.5	<0.004	<0.3	0.2	0.04	<0.06

Site	Chloride	Sulfate	Methylene Blue Active Substances	Hardness as $CaCO_3$	Turbidity (NTU)	$KMnO_4$
GDM	2.13	3	<0.04	79	1	3
No GDM	1.94	3.38	<0.04	76.4	1	2.4
Control	5	7	<0.04	80	39.5	11.05

Chemical parameter concentrations as mg/L, except Hardness (mg $CaCO_3$/L), Turbidity (NTU), or as listed within the column. No GDM was untreated water at the GDM school site. Control was the school site with no water treatment system.

3.3. Student Health Surveys

The surveys that had been conducted for self-reporting incidents of diarrhea among the students for both the control school and the GDM installation site indicated through Shapiro–Wilk tests that the data sets were normally distributed (the data are not shown). Comparing the initial period (defined as 1 to 6 weeks after the GDM installation) compared to the late period of sampling post-GDM installation (7 to 13 weeks, the surveys conducted from the study's mid-point to conclusion), a Welch Two Sample t-test indicated a significant difference in the mean incidence of diarrhea among the students ($p = 0.018$), with means of 0.0768 and 0.0519 for the initial period and late period, respectively.

The mean incidence of diarrhea for students at the control school was 0.0773, and when compared to the initial period at the GDM site, had no significant difference in incidences of diarrhea ($p = 0.968$). However, when comparing the late period of the GDM site to the control school, there was a significant decline in the mean proportions of self-reporting incidents of diarrhea ($p = 0.023$). The median values for the control school and the GDM school, both initial and late periods, are presented in Figure 3.

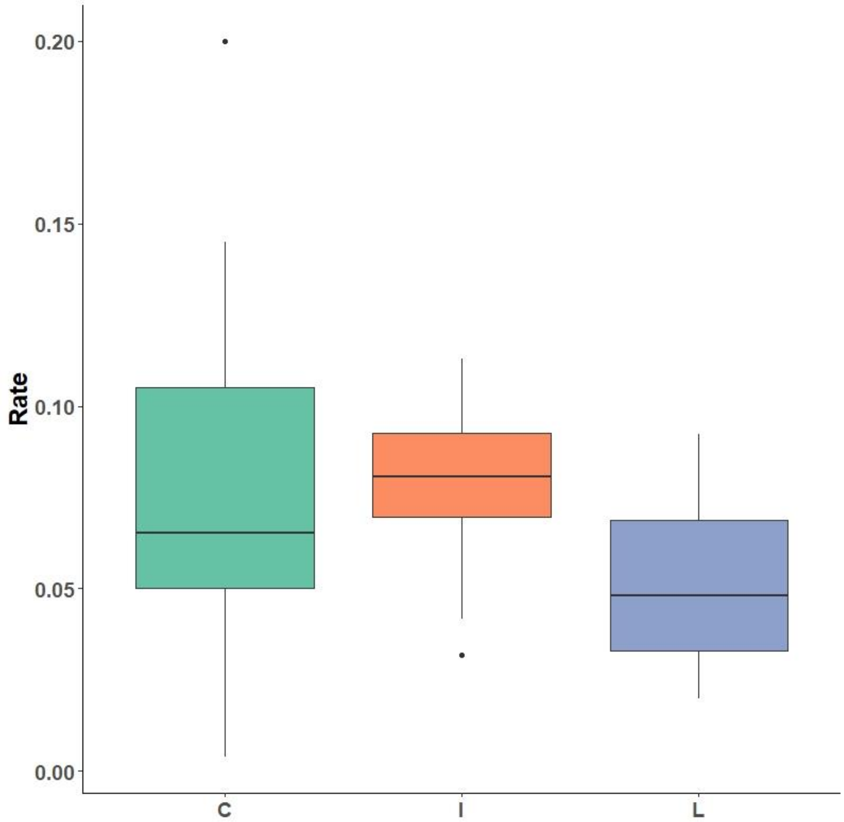

Figure 3. Incidences of diarrhea for students at the control and GDM school sites. GDM status indicates the control site (C), initial 1–6-week survey period at the GDM site after installation (I), or late survey period (7–13 weeks) at the GDM site post-installation (L). Whiskers for box plots represent upper and lower quartiles. Rate represents the proportion of students with self-reported diarrhea.

4. Discussion

The overall water quality for the chemical parameters was high for both schools, likely due to the watersheds not being heavily influenced by industrial runoff and having a lower population density in the region, despite their proximity to the coast. One study of groundwater quality in Panggang Cay, an Indonesian island city, observed increased electrical conductivity and elevated levels of Ca, Mg, K, Na, Cl, and total coliforms, with the authors suggesting that salinity encroachment was the greatest influence of poor groundwater quality in the area [22]. The water quality of the school sites was also better than another study analyzing mountain springs in central Java, as a study by Erlinawati et al. observed that levels of nitrate (17.35 mL/L) and TDS (229 mg/L) exceeded the water quality standards from a sampling of 30 wells [23]. Although one school in the current study site had elevated turbidity values, the average suspended solids were only approximately 135 mg/L (Table 5). Good water quality within the area for the study sites may also explain the relatively robust flow rate for the GDM system, which was able to maintain flow rates of 2.03–2.56 L/min throughout the study.

The greatest improvement in water quality utilizing the GDM system came in the significant reduction of bacterial contaminants, reducing the total coliforms and other fecal indicator organisms by roughly 2 logs (Table 4). It is of note that at the 6-month period there was an increase in total coliforms, which was above the Indonesian Ministry of Health threshold of 0 MPN/100 mL. Although total coliforms have long been a historical indicator of water quality, their value for determining the fecal contamination of water has diminished, as they can proliferate in the environment from the soil, water, and other sources, and their detection in the GDM system could likely indicate regrowth within the storage tank or biofilms in the water distribution line [24]. Far better indicators of the fecal contamination of water systems are *E. coli*, or fecal enteroccci, which commonly do not proliferate in the environment, and their detection in water sources offers a greater indication of diarrheal agents [24,25], and in this study, the counts for these organisms were 0 MPN/100 mL. A similar reduction in bacterial counts was observed in a study by Ding et al., where the authors observed a 95% reduction in heterotrophic bacterial counts of filtered rainwater [26]. Another study investigating the long-term performance of GDM filtration showed that the total bacterial counts were reduced by 1–2 logs (up to 377 days), while *E. coli* counts specifically had a 5-log reduction after filtration (297-day period) [18].

The bacterial loads in well water were similar to a more recent water quality survey in Indonesian villages. Kairunnisa et al. observed that four of eleven of the sampled sites had low total coliform counts (2-log MPN/100 mL or less), but the remaining villages had total coliform counts of 3-log MPN/100 mL or greater and similarly high levels of *E. coli* MPN counts [27]. Water sources contaminated with fecal bacteria are still a challenge for Indonesia and have an impact on the public health of the country. An investigation of clinical diarrhea cases of Indonesian children under 5 years old from 2009–2012 surveying hospitals and clinics from five cities showed that pathogenic bacteria were the cause of illness in 18.82% of cases [3]. Additionally, the Indonesian Ministry of Health 2018 Basic Health Survey found that the incidence of diarrhea for children under the age of 5 was approximately 11.0% [3].

While this study demonstrated a significant reduction in self-reported incidences of diarrhea for students that had access to GDM-treated water, it is important to note that the consumption of unimproved water quality outside of the school environment was not addressed and can still impact student health. Efforts to improve water quality at home are likely an important factor to implement a holistic solution to providing safe drinking water to rural communities. However, methods for implementing household water treatment systems also have challenges, and the importance of centralized community systems should not be trivialized, even if they are only part of the water consumption practices of children. Improvement of access to basic water, sanitation, and hygiene in Indonesia has made great strides, increasing from roughly 55% in 2011 to 86–92% in 2020 [17]. Still, improving water quality is an important factor for public health in Indonesia, as only 14.4% of the rural inhabitants in 2020 had access to drinking water that was deemed safe to consume [4].

The long-term applications of GDM systems have been implemented using surface water sources able to maintain stable filtration rates for up to a year with a water flux of between 2.95 and 5.2 L/h [28]. The utilization of other pre-treatment systems, such as sand filtration, can improve the performance of GDM systems [29]. Additionally, different membrane surface materials do have some impact on long-term filtration efficacy with surface water for periods over a year, where it is likely that the roughness of the membrane surface promotes the formation of biofilms that affect the flux stability [30]. Other studies have shown that biofilm formation can also improve the long-term filtration ability of GDM systems [29,31]. Yet, there are some limitations with GDM systems, as they cannot filter chemical contaminants or viruses due to their pore size. However, with certain watersheds, this may not be an issue as with the study presented here, where the untreated water quality for chemical contaminants was quite good.

The material and installation cost of the GDM system was approximately $3000 USD. As the system requires no energy to use and minimal maintenance (a bi-yearly draining of the initial sedimentation tank) and has an expected 8-year lifetime, a conservative estimate for the costs of the system would be $375 USD annually. Conversely, from conversations with participating Indonesian schoolmasters for the study, the school with the installed GDM system purchases 2280 L water per month (20 working days) at a cost of 18.000 IDR per 19 L. This results in 2,160,000 IDR or approximately $150 USD a month being spent on bottled water for students and staff, compared to $31.25 per month for the GDM system. While there is a substantial upfront cost for purchasing and installing a GDM system, over time there are significant cost savings compared to consuming bottled water. A peripheral cost saving for households is also the prevention of diarrheal disease for young children, as studies in Indonesia estimate that indirect household costs (caregiver loss of income and direct non-medical costs) for acute incidents of diarrhea are $9.90 USD [32]. However, the accurate estimation for the out-of-pocket cost savings of individual students based on the survey data is problematic, as there may have been some confusion among the participants with interpreting differences between Bought and Bottled water (where students may have considered Bought water the bottled water supplied by the school). Regardless, it is of note that student consumption of treated water on-site at the school increased substantially over time after the GDM installation (Table 3).

Point-of-use water treatments can have a large impact on reducing diarrhea illness in developing countries [33]. This study demonstrates that GDM water filtration can be a sustainable technology, providing Indonesian communities with effective, energy-free, low-maintenance water treatment systems. Further, compared to other solutions such as procuring commercially available bottled water, there can be cost savings over time by utilizing GDM systems.

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References

1. You, D.; Hug, L.; Ejdemyr, S.; Beise, J. *Levels and Trends in Child Mortality: Report 2012*; United Nations Children's Fund: New York, NY, USA, 2012.
2. Prüss-Ustün, A.; Bartram, J.; Clasen, T.; Colford, J.M., Jr.; Cumming, O.; Curtis, V.; Bonjour, S.; Dangour, A.D.; De France, J.; Fewtrell, L. Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: A retrospective analysis of data from 145 countries. *Trop. Med. Int. Health* **2014**, *19*, 894–905. [CrossRef] [PubMed]
3. Puspandari, N.; Amalia, N.; Hartoyo, Y.; Nursofiah, S.; Sunarno, S.; Sariadji, K.; Soekarso, T.; Febrianti, T.; Khariri, K.; Muna, F. Enteric Pathogen among Children under Five Years Old with Diarrheal Diseases in Indonesia. In *IOP Conference Series: Earth and Environmental Science, 2021*; IOP Publishing: Bristol, UK, 2021; p. 012098.
4. Sutomo, S.; Sagala, S.; Sutomo, B.; Winarti, S.; Sanjaya, G. Accelerating the Provision of Safe Water Supply in Urban and Rural Areas of Indonesia. *Kesmas J. Kesehat. Masy. Nas.* **2021**, *16*. [CrossRef]
5. Walker, C.F.; Black, R. Diarrhoea morbidity and mortality in older children, adolescents, and adults. *Epidemiol. Infect.* **2010**, *138*, 1215–1226. [CrossRef] [PubMed]
6. Deshpande, A.; Miller-Petrie, M.K.; Lindstedt, P.A.; Baumann, M.M.; Johnson, K.B.; Blacker, B.F.; Abbastabar, H.; Abd-Allah, F.; Abdelalim, A.; Abdollahpour, I. Mapping geographical inequalities in access to drinking water and sanitation facilities in low-income and middle-income countries, 2000–17. *Lancet Glob. Health* **2020**, *8*, e1162–e1185. [CrossRef]
7. Reiner, R.C., Jr.; Wiens, K.E.; Deshpande, A.; Baumann, M.M.; Lindstedt, P.A.; Blacker, B.F.; Troeger, C.E.; Earl, L.; Munro, S.B.; Abate, D. Mapping geographical inequalities in childhood diarrhoeal morbidity and mortality in low-income and middle-income countries, 2000–17: Analysis for the Global Burden of Disease Study 2017. *Lancet* **2020**, *395*, 1779–1801. [CrossRef]

8. Peter-Varbanets, M.; Gujer, W.; Pronk, W. Intermittent operation of ultra-low pressure ultrafiltration for decentralized drinking water treatment. *Water Res.* **2012**, *46*, 3272–3282. [CrossRef]
9. Pronk, W.; Ding, A.; Morgenroth, E.; Derlon, N.; Desmond, P.; Burkhardt, M.; Wu, B.; Fane, A.G. Gravity-driven membrane filtration for water and wastewater treatment: A review. *Water Res.* **2019**, *149*, 553–565. [CrossRef]
10. Peter, M. *Gravity-Driven Membrane Disinfection for Household Water Treatment*; Eawag: Dübendorf, Switzerland, 2015.
11. Pooi, C.K.; Ng, H.Y. Review of low-cost point-of-use water treatment systems for developing communities. *NPJ Clean Water* **2018**, *1*, 11. [CrossRef]
12. Maheux, A.F.; Picard, F.J.; Boissinot, M.; Huppe, V.; Bissonnette, L.; Bernier, J.-L.T.; Cantin, P.; Huletsky, A.; Bergeron, M.G. Analytical limits of three β-glucosidase-based commercial culture methods used in environmental microbiology, to detect enterococci. *Water Sci. Technol.* **2009**, *60*, 943–955. [CrossRef]
13. Simpson, J.M.; Santo Domingo, J.W.; Reasoner, D.J. Microbial source tracking: State of the science. *Environ. Sci. Technol.* **2002**, *36*, 5279–5288. [CrossRef]
14. Hunter, P.R. Drinking water and diarrhoeal disease due to *Escherichia coli*. *J. Water Health* **2003**, *1*, 65–72. [CrossRef] [PubMed]
15. Saxena, T.; Kaushik, P.; Mohan, M.K. Prevalence of E. *coli O157: H7 in water sources: An overview on associated diseases, outbreaks and detection methods. Diagn. Microbiol. Infect. Dis.* **2015**, *82*, 249–264.
16. Douterelo, I.; Boxall, J.B.; Deines, P.; Sekar, R.; Fish, K.E.; Biggs, C.A. Methodological approaches for studying the microbial ecology of drinking water distribution systems. *Water Res.* **2014**, *65*, 134–156. [CrossRef] [PubMed]
17. Satriani, S.; Ilma, I.S.; Daniel, D. Trends of water, sanitation, and hygiene (WASH) research in Indonesia: A systematic review. *Int. J. Environ. Res. Public Health* **2022**, *19*, 1617. [CrossRef] [PubMed]
18. Lee, D.; Lee, Y.; Choi, S.S.; Lee, S.-H.; Kim, K.-W.; Lee, Y. Effect of membrane property and feed water organic matter quality on long-term performance of the gravity-driven membrane filtration process. *Environ. Sci. Pollut. Res.* **2019**, *26*, 1152–1162. [CrossRef] [PubMed]
19. Richard, S.A.; Barrett, L.J.; Guerrant, R.L.; Checkley, W.; Miller, M.A. Disease surveillance methods used in the 8-site MAL-ED cohort study. *Clin. Infect. Dis.* **2014**, *59*, S220–S224. [CrossRef]
20. Schmidt, W.-P.; Genser, B.; Barreto, M.L.; Clasen, T.; Luby, S.P.; Cairncross, S.; Chalabi, Z. Sampling strategies to measure the prevalence of common recurrent infections in longitudinal studies. *Emerg. Themes Epidemiol.* **2010**, *7*, 1–13. [CrossRef]
21. Knight, C.; Kaiser, J.; Lalor, G.; Robotham, H.; Witter, J. Heavy metals in surface water and stream sediments in Jamaica. *Environ. Geochem. Health* **1997**, *19*, 63–66. [CrossRef]
22. Cahyadi, A.; Fatchurohman, H.; Riyanto, I. *Groundwater Quality Analysis in Dry Seasons in Panggang Cay, Kepulauan Seribu, Jakarta, Indonesia, IOP Conference Series: Earth and Environmental Science, 2018*; IOP Publishing: Bristol, UK, 2018; p. 012001.
23. Erlinawati, D.; Wibisana, M.; Putra, D.; Titisari, A. *Analysis Water Quality of Springs on the East Slope of Mount Sumbing, Central Java, Indonesia for Sanitation Hygiene Purposes Based on the Physical and Chemical Properties, IOP Conference Series: Earth and Environmental Science, 2021*; IOP Publishing: Bristol, UK, 2021; p. 012013.
24. WHO. *Guidelines for Drinking-Water Quality*, 4th ed.; WHO: Geneva, Switzerland, 2011.
25. Jang, J.; Hur, H.G.; Sadowsky, M.J.; Byappanahalli, M.; Yan, T.; Ishii, S. Environmental *Escherichia coli*: Ecology and public health implications—A review. *J. Appl. Microbiol.* **2017**, *123*, 570–581. [CrossRef]
26. Ding, A.; Wang, J.; Lin, D.; Tang, X.; Cheng, X.; Wang, H.; Bai, L.; Li, G.; Liang, H. A low pressure gravity-driven membrane filtration (GDM) system for rainwater recycling: Flux stabilization and removal performance. *Chemosphere* **2017**, *172*, 21–28. [CrossRef]
27. Kairunnisa, D.; Hendrawan, D.; Fachrul, M.; Rinanti, A. Distribution Pattern of E. coli and Total Coliform at Tanah Sareal District, Bogor City, Indonesia. In *IOP Conference Series: Earth and Environmental Science, 2021*; IOP Publishing: Bristol, UK, 2021; p. 012030.
28. Peter-Varbanets, M.; Dreyer, K.; McFadden, N.; Ouma, H.; Wanyama, K.; Etenu, C.; Meierhofer, R. Evaluating novel gravity-driven membrane (GDM) water kiosks in schools. In Proceedings of the 40th WEDC International Conference. Local Action with International Cooperation to Improve and Sustain Water, Sanitation and Hygiene (WASH) Services, Loughborough, UK, 24–28 July 2017.
29. Derlon, N.; Mimoso, J.; Klein, T.; Koetzsch, S.; Morgenroth, E. Presence of biofilms on ultrafiltration membrane surfaces increases the quality of permeate produced during ultra-low pressure gravity-driven membrane filtration. *Water Res.* **2014**, *60*, 164–173. [CrossRef] [PubMed]
30. Lee, D.; Cha, Y.J.; Baek, Y.; Choi, S.S.; Lee, Y. Relationships among Permeability, Membrane Roughness, and Eukaryote Inhabitation during Submerged Gravity-Driven Membrane (GDM) Filtration. *Appl. Sci.* **2020**, *10*, 8111. [CrossRef]
31. Stoffel, D.; Rigo, E.; Derlon, N.; Staaks, C.; Heijnen, M.; Morgenroth, E.; Jacquin, C. Low maintenance gravity-driven membrane filtration using hollow fibers: Effect of reducing space for biofilm growth and control strategies on permeate flux. *Sci. Total Environ.* **2022**, *811*, 152307. [CrossRef] [PubMed]
32. Thobari, J.A.; Mulyadi, A.W.E.; Watts, E.; Carvalho, N.; Debellut, F.; Clark, A.; Soenarto, Y.; Bines, J.E. Direct and indirect costs of acute diarrhea in children under five years of age in Indonesia: Health facilities and community survey. *Lancet Reg. Health West. Pac.* **2022**, *19*, 100333. [CrossRef]
33. Fewtrell, L.; Kaufmann, R.B.; Kay, D.; Enanoria, W.; Haller, L.; Colford, J.M., Jr. Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: A systematic review and meta-analysis. *Lancet Infect. Dis.* **2005**, *5*, 42–52. [CrossRef]