Performance and cost comparison of a gravity-driven free-end membrane and other water filtration systems for household water treatment

Jonghun Lee, Kwang Pyo Son, Pyung-Kyu Park and Soo Hong Noh

ABSTRACT

Various types of gravity-driven membrane (GDM) systems have been developed to solve household water treatment problems. A gravity-driven free-end membrane (E-GDM) system was developed to mitigate the deposition of cake on the membrane more effectively than other commercialized GDM systems. The E-GDM system was manually operated with permeability of 12.94 and 1.75 L/m^2/h/kPa for a kaolin suspension and a wastewater treatment plant influent sample, respectively, showing the highest average permeability and flow rate among all GDM systems. The GDM systems tested in this study met the daily minimum water requirement of a five-person family, except for a case in which wastewater treatment plant influent is filtered using a commercialized GDM system. According to permeability data from an accelerated cleaning test, the E-GDM system can be expected to guarantee 79,858 L of safe drinking water during its lifetime. The annual cost of the E-GDM system was assessed to be US$5.71 per household, which allows household water treatment in low- and middle-income countries.

Key words | cost analysis, free-end filter, gravity-driven membrane (GDM), household water treatment, purchasing power, water filtration

Jonghun Lee
Kwang Pyo Son
Pyung-Kyu Park
Soo Hong Noh (corresponding author)
Department of Environmental Engineering,
Yonsei University,
Yonseidae-gil 1, Wonju, Gangwon 26493,
Republic of Korea
E-mail: *drnoh@yonsei.ac.kr*

ABBREVIATIONS AND SYMBOLS

ADWPPH	Average drinking water purchasing power of each household
DOC	Dissolved organic carbon
E-GDM	Gravity-driven free-end membrane
GDM	Gravity-driven membrane
GDP	Gross domestic product
LMH	Liter per square meter per hour
NTU	Nephelometric turbidity unit
A	Membrane area
J	Flux
Q	Flow rate
t	Time

doi: 10.2166/ws.2020.007

INTRODUCTION

In the early 21st century, the United Nations (UN) established the Millennium Development Goals (MDGs) to prevent absolute poverty and protect the weak around the world. There were noticeable improvements in poverty, primary education, child mortality, disease prevention, and drinking water due to the MDGs. Despite these significant efforts, several problems remain to be solved, one of which is sanitation (UN 2015). With regard to drinking water, the UN set a goal (Target 7C) to provide safe drinking water. Due to continuous effort toward the achievement of the 7C goal, approximately 91% of people around the world have access to improved drinking water sources, such as tap water, safe boreholes, and bottled water from water vendors. However, the remaining 9% (about 663 million people) continue to fetch water from unprotected wells or surface water sources, with half of these people living in sub-Saharan Africa and one-fifth living in South Asia (UN 2015). Even for the larger group of 91%, in some regions water quality still remains a serious problem (Ahmad 2017).

There are some seasonal variations with regard to water sources. A large number of people depend on drinking water vendors; however, the water from these vendors is often not safe to drink. In Nigeria it was reported that water is associated with color, odor, and taste problems and that more than 86% of people have suffered from water-related diseases (Ahmad 2017). The supply of tap water can be intermittent due to insufficient infrastructure, high operational costs, distribution system deficiencies, and pipe breakages (Galaitsi *et al.* 2016). The quality of tap water can be threatened by turbid matter and bacteria, which flows into the broken pipes. These issues force consumers to rely on household water treatment strategies to ensure safe drinking water.

Various types of household water treatment systems have been developed for low- and middle-income countries. Filtration is one of the most widely used water treatment technologies, not only for conventional water treatment plants but also for household water treatment systems. This method physically removes bacteria and pathogens depending on the size of the filter, which can vary from quality submicron range to a few microns (Cheryan 1998). Several researchers have demonstrated that the filtrate quality and quantity of a gravity-driven membrane (GDM) filter are better than those of other water purification technologies used in low- and middle-income countries. Clasen *et al.* (2009) reported that a hollow fiber GDM unit could produce 8.8 L of biologically safe water per hour when operated under hydraulic pressure. Peter-Varbanets *et al.* (2010) developed and operated an ultrafiltration flat-sheet GDM system with an average flux of 4–10 L/m^2/h (LMH) at a hydraulic pressure of 6.5 kPa for various water conditions, corresponding to 24–60 L/d for 0.25 m^2. Frechen *et al.* (2011) introduced a flat-sheet GDM system that could be operated at a hydraulic pressure of 8 kPa with a stable flux of 5 LMH and a filtrate flow rate of 20 L/d without any maintenance. A gravity-driven free-end membrane (E-GDM) system was developed to mitigate fouling with various manual cleaning methods. The E-GDM system is a point-of-use, gravity-driven drinking water system with an individually sealed microfiltration hollow fiber module and a 20-L plastic jerrycan widely used around the world. Lee *et al.* (2019a) introduced an optimum manual cleaning method with 70 vertical repetitions for the middle region of the module and 70 vertical repetitions near the module header part. They also demonstrated that the E-GDM system could produce enough filtrate water for drinking and cooking for a five-person family in low- and middle-income countries. In another study, Lee *et al.* (2019b) investigated dissolved organic carbon (DOC) removal from filtrate water with the addition of powdered activated carbons in an E-GDM system. These previous studies focused on the optimal operation of an E-GDM system. However, there is little research on the performance comparison of membrane filtration systems in low- and middle-income countries. In terms of cost, some of the researchers reported the price of water filtration systems for low- and middle-income countries (Brown & Sobsey 2007; Clasen 2009; Carvalho *et al.* 2011). However, there was a lack of discussion on the monetary possibility of introducing the filtration systems for drinking water to low- and middle-income countries within their budgets. In this study, therefore, the filtration performance and the cost comparison of an E-GDM system and other commercialized water filtration systems were investigated on the premise of applications in low- and middle-income countries.

The aims of this study are as follows: (1) to evaluate the permeability, flux, and volumetric flow rate of an E-GDM system compared to those of two commercialized hollow fiber GDM systems using a kaolin suspension and a wastewater treatment plant (WWTP) influent, (2) to investigate the lifespan of the E-GDM system and its filtration cost, and (3) to evaluate the purchasing power for household water treatment systems in low- and middle-income countries to verify the suitability of the E-GDM system for such countries.

MATERIALS AND METHODS

Feed water characteristics

A kaolin suspension was used as one of the types of feed water in comparison tests to simulate a water source containing highly turbid and low organic matter. It was prepared by dispersing 4 g of kaolin powder (RC-15, Edgar Minerals, Hawthorne, Florida, USA) into 20 L of groundwater. The average turbidity and DOC concentration of the groundwater were 2.046 nephelometric turbidity units (NTU) and 0.876 mg/L, respectively. The average turbidity of the kaolin suspension was 118.1 NTU, and *Escherichia coli* (*E. coli*) was not detected in the suspension (Table 1). The kaolin suspension was employed as a source of high concentration of suspended solids to simulate the contaminated surface water during the rainy season in Southeast Asia (Prathumratana *et al.* 2008).

The WWTP influent, containing relatively high concentrations of suspended solids and organic matters, was used as another water source to simulate highly contaminated surface water during dry seasons in low- and middle-income countries (GLOWS-FIU 2014). Water samples were taken from the influent stream of a conventional WWTP located in the city of Wonju in the Republic of Korea. The average turbidity and DOC concentration of the influent were 117.6 NTU and 37.41 mg/L, respectively. *E. coli* colonies were 2,290,000 colony forming unit (CFU)/100 mL.

Table 1 | Water quality parameters of the kaolin suspension and WWTP influent used in this study

	Kaolin suspension	**WWTP influent**
Suspended solids (mg/L)	–	135.3 ± 29.5
Turbidity (NTU)	118.1 ± 15.0	117.6 ± 46.5
DOC (mg/L)	0.876	37.41
E. coli (CFU/100 mL)	Not detected	2,290,000

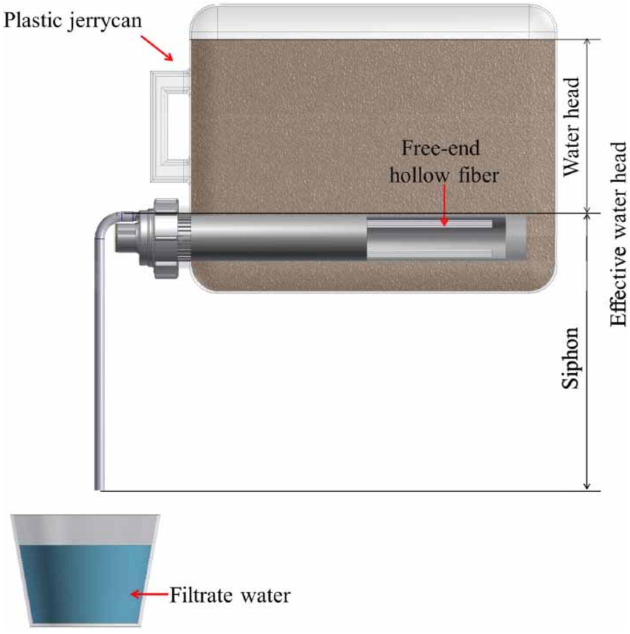

Figure 1 | Schematic diagram of E-GDM system.

Set-up and operation of the E-GDM system and two commercial GDM systems

An E-GDM system and two different commercial GDM systems (GDM-1 and GDM-2) were used in this study. Figure 1 shows the schematic diagram of the E-GDM system. The E-GDM system consisted of a free-end membrane module and a 20-L plastic jerrycan of the type widely used around the world. The free-end membrane module consisted of hollow fibers, one end of which was sealed individually as opposed to fibers being potted together, and was allowed to move freely (Kwon *et al.* 2008). The membrane length and area were 320 mm and 0.36 m^2, respectively (Table 2). The E-GDM system was operated with an effective water head from 4.51 kPa to 3.23 kPa and with raw water filtered from outside to inside. The water flux was measured at the beginning and the end of each batch (Lee *et al.* 2019a). Manual cleaning was accomplished with two different cleanings protocols: cleaning between batch filtrations and maintenance cleaning after 15 batches of operation. The cleaning between batch filtrations was carried out with the jerrycan containing 20 L of feed water by performing ten vertical shaking movements after three twisting movements. The maintenance cleaning was carried out with 70 vertical shaking movements for the middle region of the housing part and an additional 70 vertical shaking movements near the header part in a bucket containing clean groundwater (Lee *et al.* 2019a). Chemical cleaning was carried out in a separate experiment to recover the permeability of the membrane module to the greatest extent possible and to analyze the module lifetime by submerging the module for 12 h in 3,000 mg/L of a sodium hypochlorite solution. A combination of maintenance and chemical cleaning was implemented after every five batches. Because the permeability trend when using the WWTP influent did not

Table 2 | Specifications of the end-free GDM (E-GDM) system and two commercialized GDM systems (GDM-1 and GDM-2)

Unit	E-GDM	GDM-1	GDM-2
Membrane type	Hollow fiber (End-free)	Tubular	Hollow fiber
Membrane material	Polyvinylidene fluoride (PVDF)	Polysulfone (PS)	Polyethersulfone (PES)
Pore size (μm)	0.157	0.02	0.015
Outer/inner diameter (mm)	1.22/0.87	4/0.78	0.85/0.4
Effective membrane length (mm)	320	350	220
Membrane area (m^2)	0.36	0.20	0.29
Pure water permeability at 20 °C (LMH/kPa)	13.63	16.58	4.12
Filtration function	Outside-in	Outside-in	Inside-out

change significantly after two batches (see Figure 2), the operation of five batches was sufficient to foul the membrane, thus necessitating the maintenance and chemical cleaning process.

For GDM-1, the membrane length was 350 mm and the membrane area was calculated to be 0.20 m^2. GDM-1 could be operated by gravity feeding as well as with a hand pump, which increases filtration pressure by increasing the pressure inside of the container. However, in this study, it was operated by gravity feeding with an effective water head ranging from 5.69 kPa to 3.92 kPa. Raw water was filtered from outside to the inside of a tubular membrane. The water flux was measured at the beginning and the end of each batch. Maintenance cleaning was carried out by rinsing the outside of the filter with clean running water, as described in the operating manual (Icon Lifesaver 2017).

GDM-2 has a membrane length and area of 220 mm and 0.29 m^2, respectively. This system was operated with an effective water head ranging from 132 kPa to 0 kPa and with raw water filtered from the inside a fiber bundle to the outside. The water flux was measured once at the beginning of each batch. Maintenance cleaning was conducted by squeezing a backwashing apparatus attached to the filter body (Clasen *et al.* 2009).

Water flux and permeability calculations

The water flux of filtrate was calculated based on the quantity of the filtrate, effective membrane area, and filtration time, as shown in Equation (1). The calculated flux was corrected to J_{20} at 20 °C with Equation (2) (Fan *et al.* 2006):

$$J = Q/A/t \tag{1}$$

$$J_{20} = J \times 1.025^{(20-T)} \tag{2}$$

where J is the water flux (LMH), Q is the quantity of the filtrate (m^3), A is the effective membrane area (m^2), t is the filtration time (h), and T is the temperature of the filtrate (°C). The permeability$_{20}$ (LMH/kPa) value was determined by dividing J_{20} by the transmembrane pressure (kPa), which was calculated by summing the water head and the siphon pressure (Lee *et al.* 2019a), as follows:

$$\text{Permeability}_{20} = J_{20}/\text{transmembrane pressure} \tag{3}$$

Analytical methods

The feed water and filtrate were analyzed to confirm the water quality. Turbidity was measured using a turbidimeter (2100Q Portable Turbidimeter, Hach, USA). The amount of suspended solid was determined by filtering the raw water with 0.45 μm glass microfiber filters (GFC-047, Whatman, UK) using a vacuum pump according to a standard method (2,540 Solids, Standard method 1999). *E. coli* was analyzed using Petrifilm *E. coli*/coliform count plates (6414, 3M, USA) following the method described by Hörman & Hänninen (2006).

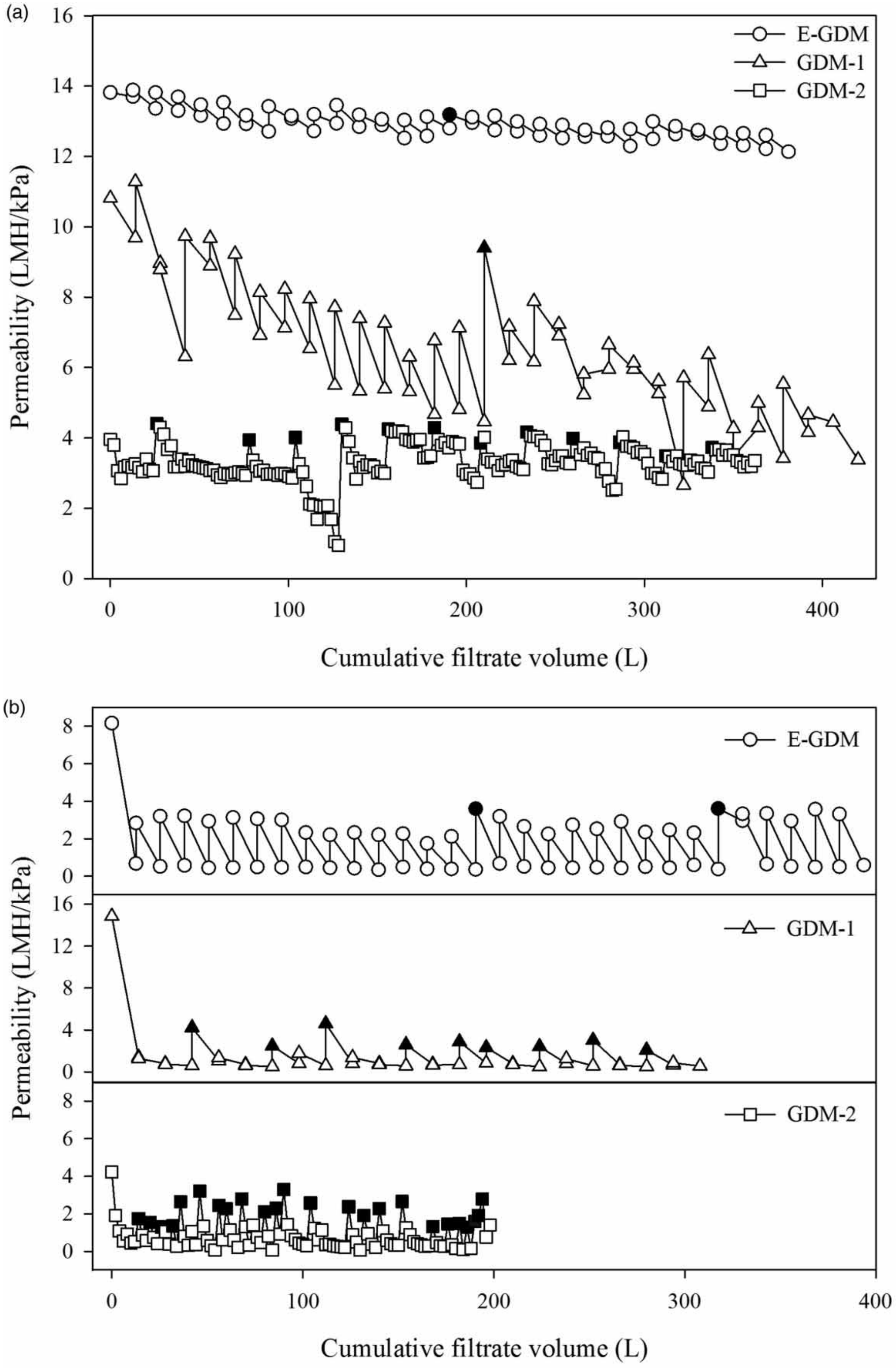

Figure 2 | Variations in the permeability as a function of the cumulative filtrate volume of E-GDM (circle), GDM-1 (triangle), and GDM-2 (square) with (a) 200 mg/L of the kaolin suspension and (b) the WWTP influent. The closed symbols reveal the permeability or flow rate after maintenance cleaning. Chemical cleaning was not applied.

Purchasing power and filtration cost estimation

The gross domestic production (GDP) data were obtained from the World Economic Outlook Database to calculate the purchasing power for drinking water (International Monetary Fund (IMF) 2017). The household size for low- and middle-income countries was assumed to be five in this study (UN 2017). People who live in low- and middle-income countries are assumed to spend less than 1% of GDP on safe drinking water (United Nations Development Programme 2006). The average drinking water purchasing power of each household (ADWPPH) was calculated by multiplying GDP per capita by 1% and then by five people. Regional classification utilized the IMF emergency market and developing countries criteria.

The filtration cost (US$/L) was estimated using the capital cost (US$), replacement cost (US$), and guaranteed water production (L) values. The daily cost per household (US$/day/household) was calculated by multiplying the filtration cost by 25 L, which is minimum water requirement for daily drinking and cooking for a five-person family (Tumwine *et al.* 2002). The annual cost per household (US$/year/household) was calculated by multiplying the daily costs per household by 365 days.

$$\mathrm{ADWPPH} = \mathrm{GDP} \times 0.01 \times 5\,\mathrm{persons} \tag{4}$$

$$\text{Filtration cost} = \frac{\text{Capital cost (US\$)} + \text{Replacement cost (US\$)}}{\text{Guaranteed water production (L)}} \tag{5}$$

$$\text{Daily cost per household} = \text{Filtration cost} \times 25\,\mathrm{L} \tag{6}$$

$$\text{Annual cost per household} = \text{Daily cost per household} \times 365\,\mathrm{d} \tag{7}$$

RESULTS AND DISCUSSION

Consecutive batch filtration with a kaolin suspension and a WWTP influent

Figure 2 shows the permeability of each GDM system as a function of the cumulative filtrate volume for tests with the 200 mg/L kaolin suspension and the WWTP influent. The closed symbols indicate the permeability after maintenance cleaning.

Figure 2(a) shows the permeability variation of each GDM system with the kaolin suspension. For the E-GDM system, the initial permeability was 13.8 LMH/kPa. The permeability decreased to 87.8% of the initial permeability during the filtration of 381 L, after which the permeability increased to 90.7% after maintenance cleaning was conducted once during the operation of the system. For GDM-1, the initial permeability was 10.8 LMH/kPa. The permeability in this case decreased to 31.2% of the initial water permeability during the filtration of 420 L. The permeability increased to 61% due to the maintenance cleaning step. The initial permeability of GDM-2 was 3.96 LMH/kPa, and the permeability decreased to 84.8% of the initial water permeability during the filtration of 362 L. After conducting maintenance cleaning 12 times, the permeability was restored to the initial permeability.

Figure 2(b) shows the variation of the permeability of each GDM system with the WWTP influent. The permeability of the three GDM systems decreased sharply to less than 1 LMH/kPa during the first batch due to the high turbidity and DOC concentration of the WWTP influent. The permeability of the E-GDM system decreased to 7.2% of the initial permeability during the filtration of 394 L, and the permeability increased to 44.1% after each of the two maintenance cleanings. The permeability of GDM-1 decreased to 3.7% of the initial permeability during the filtration of 308 L. Maintenance cleaning was conducted nine times during the filtration process, and the permeability increased to approximately 19.9%. The permeability of GDM-2 decreased to 2.6% of the initial permeability during the filtration of 200 L. Maintenance cleaning was conducted 24 times in this case, leading to a permeability increase of 46.3%.

Figure 3 shows the variation of the flux at 20 °C for each GDM system as a function of the cumulative filtrate volume for tests with the 200 mg/L kaolin suspension and the WWTP influent. The closed symbols indicate the flux after maintenance cleaning.

Figure 3(a) shows the flux variation of each GDM system with the kaolin suspension. For the E-GDM system, the initial flux was 63.7 LMH and, because of the water pressure, the flux increased and decreased repeatedly and the flux decreased to 40.5 LMH during the filtration of 381 L. After maintenance cleaning, the flux increased to 95.4% compared to the initial flux. For GDM-1, the initial flux was 61.5 LMH and the flux decreased to 13.3 LMH during the filtration of 420 L. The flux recovered to 86.9% compared to the initial flux due to maintenance cleaning. For GDM-2, the initial flux was 52.4 LMH, and the flux decreased to 84.9% of the initial flux during the filtration of 362 L.

Figure 3(b) shows the variation of the flux of each GDM system with the WWTP influent. The flux of the E-GDM system decreased from 37.6 LMH to 1.1 LMH during the filtration of 394 L. The flux increased to an average of 44.0% after each of the two maintenance cleanings. For GDM-1, the flux decreased from 84.5 LMH to 2.2 LMH during the filtration of 308 L, and after nine rounds of maintenance cleaning, the flux increased to 19.9% on average, compared to the initial flux. For the GDM-2, the flux decreased from 55.8 LMH to 18.7 LMH during the filtration of 200 L. Maintenance cleaning was conducted 24 times, and the flux increased to approximately 51.1% compared to the initial flux.

Figure 4 shows the variation of the flow rate of each GDM system as a function of the cumulative filtrate volume for tests with the 200 mg/L kaolin suspension and the WWTP influent. The closed symbols indicate the flow rate after maintenance cleaning.

Figure 4(a) shows the filtration flow rate versus the cumulative filtrate volume of each GDM system. For the E-GDM system, the flow rate fell from 23.04 L/h to 14.64 L/h during the filtration of 381 L. The average flow rate was 17.96 L/h. The flow rate of GDM-1 decreased from 12.35 L/h to 2.68 L/h during the filtration of 420 L. The average flow rate was 6.28 L/h. For GDM-2, the flow rate was reduced from 15.63 L/h to 13.39 L/h during the filtration of 362 L. The average flow rate was 12.90 L/h. The mean flow rate after filtration of over 18,000 L, which is the guaranteed filter life, was 8.8 L/h for artificial water that contained 15 NTU of turbid matter and 5 mg/L of humic acid (Clasen *et al.* 2009).

Figure 4(b) shows the filtration flow rate according to the filtration volume of each GDM system. The flow rate of the E-GDM system decreased from 13.60 L/h to 0.71 L/h during the filtration of 394 L, and the average flow rate was 2.81 L/h. The flow rate of GDM-1 decreased from 16.77 to 0.42 L/h during the filtration of 308 L, and the average flow rate was 1.65 L/h. The flow rate of GDM-2 decreased from 16.40 to 5.49 L/h during the filtration of 200 L, and its average flow rate was 3.94 L/h.

In summary, the E-GDM system showed the highest average permeability and thus would facilitate the highest production level at the same pressure condition among the GDM systems tested here. Tumwine *et al.* (2002) reported that 5 L of safe water per capita is needed for daily drinking and cooking in low- and middle-income countries and that an additional 7 L per capita is needed for bathing and personal hygiene. For a five-person family, 25 L of safe water is required for drinking and cooking. A total of 60 L of water is needed for drinking, cooking, bathing, and personal hygiene. The E-GDM, GDM-1, and GDM-2 systems could produce 215.52 L, 75.36 L, and 154.8 L of filtrate, respectively, when operating during 12 h of daytime. For filtration with the kaolin suspension, all the GDM systems could meet the minimum water requirement and family basic hygiene requirement. For the filtration with WWTP influent, The E-GDM, GDM-1, and GDM-2 systems could produce 33.74 L, 19.80 L, and 47.28 L of filtrate, respectively, during operation for 12 h of daytime. The E-GDM and GDM-2 systems could meet the daily minimum water requirement for a five-person family. However, GDM-1 could not do so for such a family during 12 h of operation.

The feed water turbidity of the kaolin suspension was 118.1 ± 15.0 NTU, and that of the filtrate was 0.09 ± 0.03 NTU, 0.14 ± 0.04 NTU, and 0.13 ± 0.04 NTU for the E-GDM, GDM-1, and GDM-2 systems, respectively. For the WWTP influent, the turbidity of the raw water was 117.6 ± 46.5 NTU, and that of the filtrate was 0.11 ± 0.03 NTU, 0.23 ± 0.09 NTU, and 0.16 ± 0.08 NTU in the E-GDM, GDM-1, and GDM-2 cases, respectively. The *E. coli*

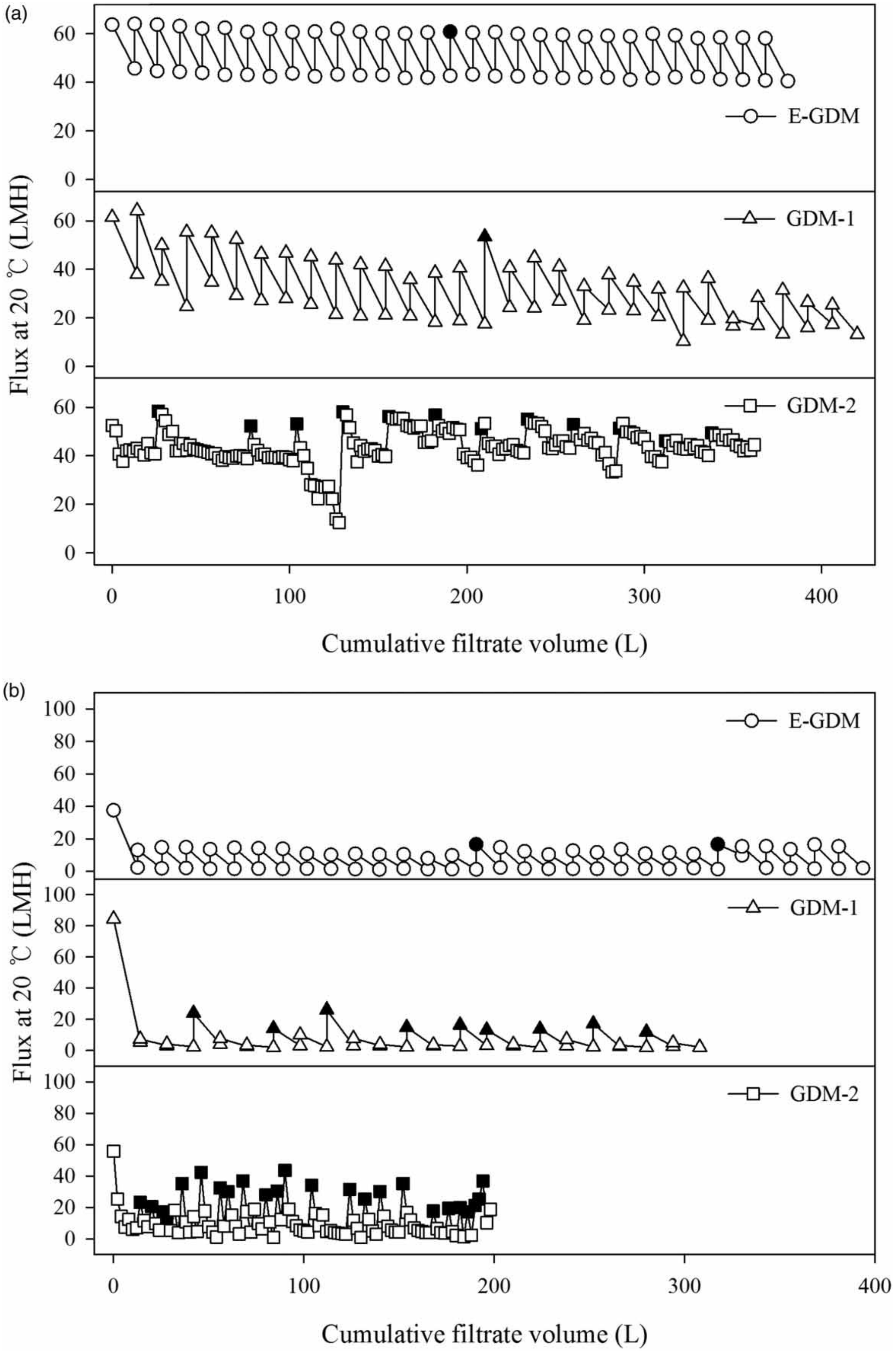

Figure 3 | Variations in the flux at 20 °C as a function of the cumulative filtrate volume of E-GDM (circle), GDM-1 (triangle), and GDM-2 (square) with (a) 200 mg/L of the kaolin suspension and (b) the WWTP influent. The closed symbols reveal the permeability or flow rate after maintenance cleaning. Chemical cleaning was not applied.

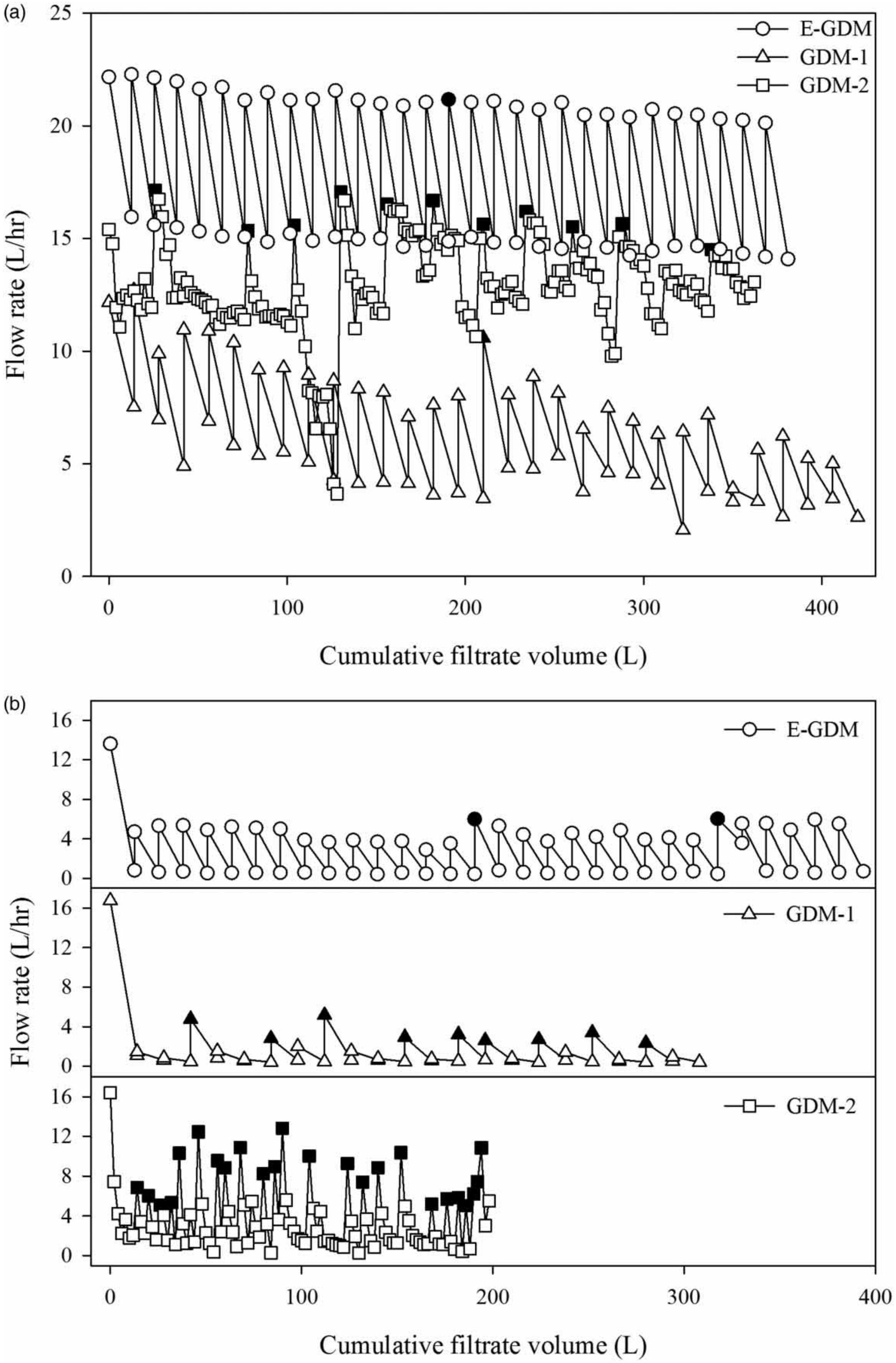

Figure 4 | Variations in the flow rate as a function of the cumulative filtrate volume of E-GDM (circle), GDM-1 (triangle), and GDM-2 (square) with (a) 200 mg/L of the kaolin suspension and (b) the WWTP influent. The closed symbols reveal the permeability or flow rate after maintenance cleaning. Chemical cleaning was not applied.

colonies were 2,290,000 CFU/100 mL in the WWTP influent, whereas *E. coli* was not detected in the filtrates of the three GDM systems. World Health Organization (WHO) regulations state that the turbidity should be less than 5 NTU, and *E. coli* should not be present in drinking water (WHO 2008). For all the filtrates here, it was therefore confirmed that the levels of turbidity and *E. coli* met the corresponding drinking water standard.

The lifespan of the E-GDM system with the WWTP influent

Membrane lifespan is one of the most important issues related to the cost of the membrane system. Figure 5 shows the permeability changes of the E-GDM system during filtration of the WWTP influent with maintenance and chemical cleanings every five batches. The cleanings were effective for maintaining the operation of the module over 100 batches, but the permeability values after the chemical cleanings decreased gradually, as shown by the gray circles in Figure 5. The maximum lifespan of the E-GDM system was estimated by extrapolating the permeability trend and determining the number of chemical cleanings until the time when the flow rate after chemical cleaning was expected to be less than 25 L/d, which corresponds to an average permeability of 0.62 LMH/kPa for the E-GDM system. It was determined that 131 cleanings would be necessary. Considering that the system could complete 48 batches without any chemical cleaning, as shown in Figure S1 in the Supporting Information, the estimated maximum lifespan was 131 × 48 batches (between chemical cleanings), i.e. 6,288 batches, corresponding to 8.61 years at two batches (25 L) per day. Considering the guaranteed filtration quantities of GDM-1 and GDM-2 were 10,000 L and 18,000 L, respectively, and thus the guaranteed membrane lifespans for GDM-1 and GDM-2 provided by each manufacturer were 1.10 years and 1.97 years when filtrating 25 L/d, respectively, it was concluded that the E-GDM system could be operated 7.82 and 4.37 times longer than GDM-1 and GDM-2, respectively.

Filtration cost comparison

Table 3 shows the filtration cost of the GDM systems and other filtration systems for household water treatment. The

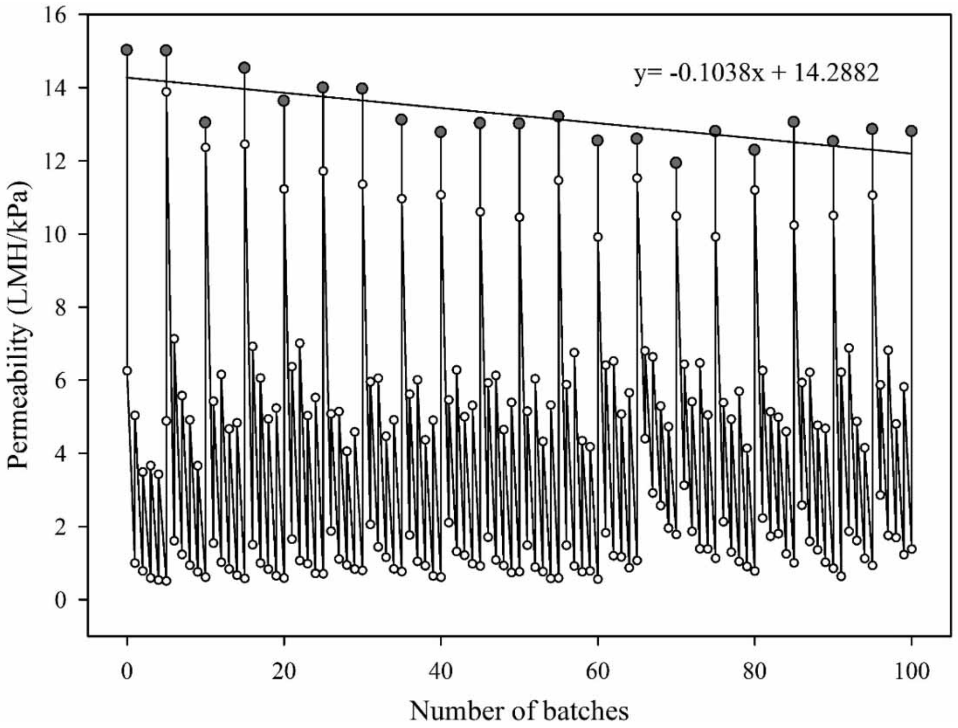

Figure 5 | Estimation of the lifetime of the E-GDM with 3,000 ppm sodium hypochlorite chemical cleanings. Gray circles denote the permeability after maintenance and chemical cleaning.

Table 3 | Cost comparison of filtration systems for household water treatment

	E-GDM	GDM-1	GDM-2	Biosand filter	Ceramic pot filter	Personal membrane filter
Capital cost (US$)	50	265.5	69.09	12–40	7.5–9.5	19.95
Replacement cost (US$)	–	130.1	–	–	2.5	–
Filtration cost per 1,000 L (US$/1,000 L)	0.63	39.56	3.84	–	1.2	4.99
Annual cost per household (US$/year/household)	5.71	360.99	35.02	5.48	11	45.51

capital cost requirements of the E-GDM, GDM-1, and GDM-2 systems were US$50, US$265.5, and US$69.09, respectively. The capital cost of GDM-1 was 5.3 times higher than that of the E-GDM system. The filter of the GDM-1 system should be replaced after 10,000 L of filtration, at a cost of about US$130/filter. The filtration cost was calculated using the corresponding guaranteed filtration volume from the manufacturer. The filtration costs per 1,000 L for the E-GDM, GDM-1, and GDM-2 systems were estimated at US$0.63, US$39.56, and US$3.84, respectively. Therefore, the annual costs of the E-GDM, GDM-1, and GDM-2 systems were calculated and found to be US$5.71, US$360.99, and US$35.02 per household. The annual cost per household of the E-GDM system was significantly lower than that of the other GDM systems.

The cost was also compared to those of other filtration systems for household water treatment. A biosand filter is one of simple water treatment systems for household water treatment. The capital cost has been estimated to range from US$12 to US$40 at an annual cost of US$5.48/household (Clasen 2009; Carvalho *et al.* 2011). The capital cost for a ceramic pot filter is relatively low compared to those of other filtration systems. However, it is fragile and has a flow rate of 1–3 L/h, even for low turbid water (Brown & Sobsey 2007). The annual cost was estimated to be US$11/household; however, with filter replacement instead of the purchase of a new filter, the estimated annual cost was US$2.5/household. The capital cost of a commercial personal membrane filter was US$19.95. The annual cost was estimated to be approximately US$45.51 in such a case, which is 4.14 times higher than that of the ceramic pot filter. The annual cost of a biosand filter was similar to that of the E-GDM system; however, the costs of the ceramic pot and the personal membrane filter were 2 and 8.3 times higher, respectively.

The purchasing power of low- and middle-income countries

The purchasing power per capita per year for safe drinking water was calculated from GDP data as mentioned above. Briefly, most of the people living in sub-Saharan Africa require US$2–US$25/capita/year to purchase safe drinking water. For the West, Middle and East Africa regions, people spend US$2–US$10/capita/year. In India and in Southeast Asia, people spend US$10–US$50/capita/year. For Latin America and the Caribbean, US$25–US$100/capita/year are required (see Figure S2 in the Supporting Information).

Table 4 shows the average drinking water purchasing power by region. Sub-Saharan Africa can be classified into two groups due to the large GDP deviations by country. Class I is the group of countries for which the GDP is less than US$1,000, and class II is the group of countries for which the GDP ranges widely from US$1,000 to US$10,000. Countries for which the purchasing power exceeded US$100 were excluded for greater accuracy of the estimation during the classification step because most of these countries were those for which national incomes from tourism or oil accounted for the largest portion. The average drinking water purchasing power amounts for sub-Saharan Africa classes I and II are US$6.2 and US$26.5/capita/year, respectively. Thus, the average purchasing power amounts for a household (five people) were calculated and found to be US$31.2 and US$32.5/household/year, respectively. For Middle East Asia, North Africa, and Afghanistan, and for low- and middle-income countries in Asia and Oceania, the average purchasing power amounts were similar at US$162.5/household/year. For Latin America and the Caribbean, and for low- and middle-income countries in Europe, the average purchasing

Table 4 | Average purchasing power by regional group[a]

Region	Sub-Saharan Africa		Middle East Asia, North Africa, and Afghanistan	Low- and middle-income countries in Asia and Oceania	Latin America and the Caribbean	Middle-income countries in Europe
	Class I[b]	Class II[c]				
Average purchasing power per year per capita (US$/capita/year)	6.2	26.5	32.4	32.6	55.5	64.4
ADWPPH (US$/household/year)	31.2	132.5	162.0	163.0	277.5	322.0
Group	A	B			C	

[a] Excluded countries (with purchasing power exceeding US$100): (1) Class I and II: Seychelles and Equatorial Guinea; (2) Middle East Asia, North Africa, and Afghanistan: Qatar, UAE, Kuwait, Bahrain, Saudi Arabia, Oman, and Lebanon; (3) Low- and middle-income countries in Asia and Oceania: Brunei Darussalam and Palau; (4) Latin America and the Caribbean: The Bahamas, St. Kitts and Nevis, Trinidad and Tobago, Barbados, Uruguay, Antigua and Barbuda, Panama, Chile, Argentina, Costa Rica, and Venezuela; (5) Middle income countries in Europe: Poland, Hungary, and Croatia.

[b] Class I: GDP less than US$1,000.

[c] Class II: GDP from US$1,000 to US$10,000.

power amounts were US$277.5 and US$322.0/household/year, respectively.

Regions can be grouped according to the purchasing power. One group is sub-Saharan Africa class I, referred to here as the low purchasing power group (Group A, Table 4). This group requires, on average, US$31.2/household/year for safe drinking water. A second group is class II of sub-Saharan Africa, Middle East Asia, North Africa, and Afghanistan, as well as low- and middle-income countries in Asia and Oceania. This is referred to here as the moderate purchasing power group (Group B, Table 4). Group B spends an average of US$152.5/household/year on safe drinking water. A third group consists of Latin America and the Caribbean and middle-income countries in Europe, which is referred to here as the high purchasing power group (Group C, Table 4). Group C spends on average US$299.75/household/year for safe drinking water. For group A, three types of household water treatments can be used: a biosand filter, a ceramic pot filter, and the E-GDM system. The annual cost per household for GDM-1 and GDM-2 was higher than the purchasing power of Group A. For Group B, all types of water treatment systems can be used, except the GDM-1 and personal membrane filter. For Group C, all types of water treatment methods are feasible except the GDM-1. A consumer in this group can use two or more water treatment methods, such as chlorination (about US$2.28 to US$57.03/household/year, Carvalho *et al.* 2011) and filtration. Therefore, people in Group C are more likely to acquire safe drinking water. With regard to the capital cost of the GDM systems, the people in Group A cannot easily purchase the E-GDM, GDM-1, and GDM-2 systems directly. However, those in Group B have the potential to buy the E-GDM and GDM-2 systems directly. Only those in Group C can purchase all these systems given their spending power.

The prevalence of an inexpensive household water treatment system would help families save money, rather than having to purchase the more expensive bottled water in low- and middle-income countries. The annual cost of bottled water from a water vendor is estimated to range from US$1.3 to US$32.0/household, and the average cost has been determined to be US$16.3/household for low- and middle-income countries (Manda 2009; World Bank 2009; Ahmad 2017). According to the results here, it appears to be possible to achieve levels of the UN Sustainable Development Goals 3.3, 3.9, and 6.1 by providing low- and middle-income countries with inexpensive household water treatment systems, including the E-GDM system. This can also help to ensure better child education and improve women's human rights by reducing the time required to fetch clean water.

CONCLUSIONS

Comparative filtration tests were carried out using a kaolin suspension and a WWTP influent with the E-GDM system and two commercialized GDM systems (GDM-1 and GDM-2) for household water treatment. The E-GDM system demonstrated the highest average permeability and flow rate among the GDM systems tested for both feed water cases.

For filtration of the kaolin suspension, the E-GDM, GDM-1, and GDM-2 system met the daily minimum water requirement for a five-person family with daytime operation. For the WWTP influent, the E-GDM and GDM-2 systems met the minimum water requirement, whereas GDM-1 did not. The E-GDM system could produce turbid- and *E. coli*-free water to meet WHO guidelines, even for the WWTP influent. The ADWPPH varied regionally from US$31.2 to US$320 per year in low- and middle-income countries. Based on the purchasing power analyzed, together with the annual costs of the GDM systems, the E-GDM system with a biosand filter and a ceramic pot filter can be purchased by those in low-income countries classified according to their low purchasing power. GDM-2 can be purchased by countries with moderate to high purchasing power and GDM-1 can be purchased only by countries with high purchasing power. Therefore, the E-GDM system introduced here is competitive in terms of performance and cost compared to other commercialized GDM filters. In future, the E-GDM and other water treatment systems should be further tested at actual sites in low- and middle-income countries to confirm (1) the reduction in waterborne diseases, (2) the improvement of health and hygiene environments, and (3) the actual purchasing power of the water treatment systems for household drinking water.

ACKNOWLEDGEMENTS

This work was financially supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP), the Ministry of Trade, Industry, & Energy (MOTIE) of the Republic of Korea (No. 20184030202240), and also by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) (2016R1C1B1009544).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/ws.2020.007.

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First received 16 September 2019; accepted in revised form 1 January 2020. Available online 21 January 2020