Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.20802

91 (2017) 311–319
October

Evaluating water purification at household level in India

Benedikt M. Aumeier[a,*], Xin Jiang[a], Suzana Djeljadini[a], Patrick Smeets[b], Süleyman Yüce[a], Christian Kazner[c], Matthias Wessling[a,d]

[a]*Chair of Chemical Process Engineering, Aachener Verfahrenstechnik, RWTH Aachen University, Forckenbeckstr. 51, 52074 Aachen, Germany, Tel. +49 241 80 90596; Fax: +49 241 80 92252; emails: benedikt.aumeier@avt.rwth-aachen.de (B.M. Aumeier), xin.jiang@rwth-aachen.de (X. Jiang), suzana.djeljadini@avt.rwth-aachen.de (S. Djeljadini), sueleyman.yuece@avt.rwth-aachen.de (S. Yüce), matthias.wessling@avt.rwth-aachen.de (M. Wessling)*
[b]*KWR Watercycle Research Institute, P.O. Box 1072, 3430 BB Nieuwegein, The Netherlands, email: patrick.smeets@kwrwater.nl*
[c]*Institute of Ecopreneurship, University of Applied Sciences and Arts Northwestern Switzerland, Gründenstrasse 40, 4132 Muttenz, Switzerland, email: christian.kazner@fhnw.ch*
[d]*DWI Leibniz Institute for Interactive Materials, Forckenbeckstr. 50, 52074 Aachen, Germany*

Received 3 December 2016; Accepted 4 April 2017

ABSTRACT

Household water treatment systems play an important role in safe drinking water supply in India as safety barrier at point of use and contribute to improved public health on short and medium term. In this study, three household water purifiers that based on different principles were investigated in order to determine whether and under which conditions they can safeguard the microbial safety of drinking water. The water purifiers consisted of the following treatment trains: (i) activated carbon (AC), ultrafiltration (UF) and reverse osmosis, AC and UV irradiation; (ii) AC and UF, and (iii) AC, passive chlorine dosage and AC. They were examined in a two-phase challenge test using bacteria (*Escherichia coli*) and bacteriophages (MS2) in a laboratory environment. Under normal operation conditions filtering tap water, mean microbial reductions of 4–6 $\log_{10}$ and 0–3 $\log_{10}$ for *E. coli* and MS2 phages, respectively, were observed that therefore partly comply with WHO requirements. Reduction of protozoa (*Cryptosporidium* oocysts) was estimated based on size exclusion or chlorine exposure to be ≥2 $\log_{10}$ (membrane-based size exclusion) and <2 $\log_{10}$ (chlorine-based disinfection), respectively. To further determine their applicability for filtering water sources with higher pollution load, tap water with increased loads of organic and suspended matter simulating turbid river water (which is beyond the intended use of the systems) was studied. Only the multi-stage treatment was able to remove organics and turbidity to ≥89%. Both tested membrane-based systems suffered from rapid and severe irreversible fouling when challenged with high turbidity whereas the chlorine-based system maintained the production rate, however, at the expenses of a lower physicochemical quality. Hence, none of the tested systems was able to produce water of satisfying physicochemical and microbial quality at sufficient quantities from raw water with turbid river water quality. Therefore, it is suggested introducing mandatory standardized testing protocols and certification of household water purifiers specifying the usage conditions.

Keywords: Point of use water purification; Challenge test; Disinfection; Emerging economies

* Corresponding author.

Presented at the 13th IWA Specialized Conference on Small Water and Wastewater Systems & 5th IWA Specialized Conference on Resources-Oriented Sanitation, 14–16 September, 2016, Athens, Greece.

1. Introduction

In emerging economies, particularly in rural areas, both the hygienic situation and drinking water supply are inadequate leading to considerable occurrence of waterborne diseases like diarrhea (estimated 8.3 cases per 1,000 inhabitants and ca. 0.6 fatalities per 1,000 inhabitants in India in 2012) and others [1–5]. The majority of the population is supplied with drinking water in bottled form, from the tap, from well (including interim storage in a roof top tank) or they upgrade tap or well water at household level with an increasing share for the last option (annual Indian sales figures of minimum 3.6 million purifiers worth at least ~150 million euro [4]). Various studies concluded that household water treatment and safe storage can significantly reduce diarrheal diseases [6–12]. Microbial reduction varies with pathogen type and with low-tech treatment method (i.e., boiling, solar disinfection, chlorination, coagulation–filtration, biosand filtration and others), but is not always consistent over time [8,13,14]. Nowadays, these (traditional) household treatment methods are complemented by commercial household purifiers. The later are classified as reverse osmosis (RO, also called multi-stage), ultraviolet (UV) irradiation and offline (also called gravity because they are gravity-driven) purifiers. However, performance and reliability of these purifiers are often not certified by corresponding official authorities or testing institutions. Official guidelines and standards are available from NSF International and Water Quality Association, but certification is not mandatory and, even if tested, test results are not publicly available [15,16]. Hence, it is difficult to independently verify the manufacturers' claims. This study investigates under which conditions selected household drinking water purifiers can produce microbially safe drinking water. The systems are thus not to be ranked. The scope is rather to better understand their structural abilities and limitations by exposing them to conditions beyond their intended use.

2. Materials and methods

Three different commercially available household drinking water purifiers (each two units in two separate runs[1]) were investigated in this challenge test:

- Eureka Forbes Aquasure Xpert (Fig. 1, named system A hereafter): RO-based multi-stage purifier, electricity driven, input water pressure of 0.6–2.0 bar required; water sources: borewell, tap water and tanker; aim: desalination of brackish water (total dissolved solids [TDS] ≤ 2,000 mg/L), reduction of bacteria, viruses, protozoa, taste and odor; nominal production rate: 15 L/h; retail price: 20,999 INR (281 EUR); life span: 6,000 L (cartridges and membranes), 5,000 operational hours (UV lamp).
- Kent Gold Plus (Fig. 2, system B): ultrafiltration (UF)-based offline purifier, gravity driven (maximum driving water head ~0.15 m); water sources: tap or municipal corporation water; aim: reduction of protozoan cysts, chlorine, taste and odor; nominal production rate: 0.31 L/min; retail price: 3,000 INR (40 EUR); life span: 4,000 L or 1 year (UF membrane), 1,800 L or 6 months (activated carbon filter).
- Hindustan Unilever Ltd., Pureit Classic 14 L (Fig. 3, system C): chlorine-based offline purifier, gravity driven (maximum driving water head ~0.15 m); water sources: not specified; aim: reduction of bacteria, viruses, protozoa, taste and odor; nominal production rate: 2–9 L/h; retail price: 1,690 INR (23 EUR); life span: 1,250 L or 3 years (Germkill Processor™ – chlorine dosage unit).

The protocol of the conducted challenge test was derived from the guidelines for household drinking water purifiers of US EPA and WHO and adapted to Indian conditions [17–19]. The challenge test loadings consisted of physical parameters (turbidity/suspended solids and temperature), chemical parameters (organics and salt content) as well as microbial parameters (bacteria *Escherichia coli* and viruses MS2, hereafter called MS2 phages). According to the WHO guidelines [18] the main aim of the two-phase challenge test is to determine whether microbially safe drinking water can be produced with low additional organic and solid loading in the general phase and high respective loadings in the challenge phase representing a synthesized turbid river water (Table 1).

In each test phase water was treated according to manufacturer's instructions in laboratory environment to prevent cross-contamination. Depending on the filtration performance of the system, up to 30 L of water were produced every day approximating the minimum drinking water demand of a four-person household [13,20]. Every day the feedwater container was filled with fresh tap water and residual chlorine content was eliminated with a solution containing 1.55 mg/L sodium thioglycolate (Sigma-Aldrich, Germany) and 2.26 mg/L sodium thiosulfate (Sigma-Aldrich, Germany). Subsequently, a microbial load of about 10^5 cfu/mL *E. coli* (DSM-613/ATCC 11303) and about 2×10^4 pfu/mL MS2 phage (DSM-13767/ATCC 15597-B1) was added to the feed. *E. coli* were cultured overnight in 250 mL shake flasks at 37°C, 300 min^{-1} and 5 cm shaking diameter in German Collection of Microorganisms and Cell Cultures (DSMZ) liquid medium 1 [21]. The MS2 phages were propagated in advance according to DSMZ instructions using host *E. coli* (DSM-5695, optical density of 0.1 from log phase) on double layer agar [22].

The soft agar around the forming plaques was transferred into phage buffer (0.05 M Tris/HCl, 0.2% $MgSO_4$, 0.01% gelatin, pH 7.4), centrifuged (14,000 min^{-1}/10 min) and then filtered (0.2 μm cellulose acetate) and frozen in aliquots with 10% glycerol. Before each filtration cycle an appropriate quantity (calibrated with serial dilution) was added to the feed tank. MS2 phages are not, however, able to infect *E. coli* strain DSM-613. In the first test phase (general), this feedwater was fed to the investigated systems. In the second test phase (challenge), the pH value in the feedwater was increased with 1 M sodium hydroxide solution (Carl Roth, Germany), the temperature was set to 10°C ± 2°C, the salt content (TDS) was increased to around 1,500 mg/L by adding sea salt (Sigma-Aldrich, Germany), the dissolved organic carbon (DOC) was adjusted with humic acid sodium salt (Sigma-Aldrich, Germany) and the turbidity was increased by adding Arizona Test Dust A2 (Ellis Components, England) according to Table 1 and verified before use. The production rate

1 Only data of the second run for Kent Gold Plus was evaluated because the other one was damaged during transport (no turbidity reduction).

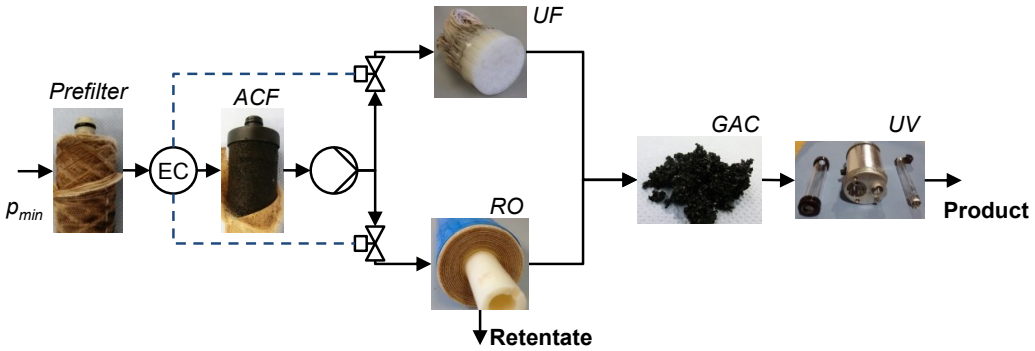

Fig. 1. Schematic of multi-stage system A including pre-filter, activated carbon filter (ACF), ultrafiltration (UF), reverse osmosis (RO), granular activated carbon (GAC) and ultraviolet light irradiation (UV); flow split according to electrical conductivity (EC).

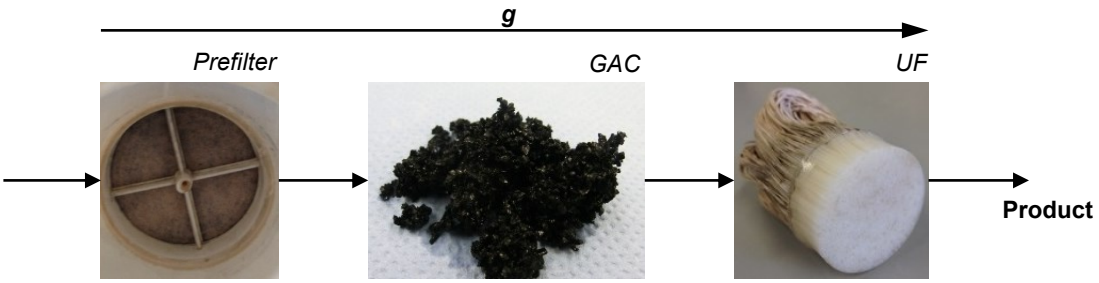

Fig. 2. Schematic of UF-based system B including pre-filter, GAC and UF.

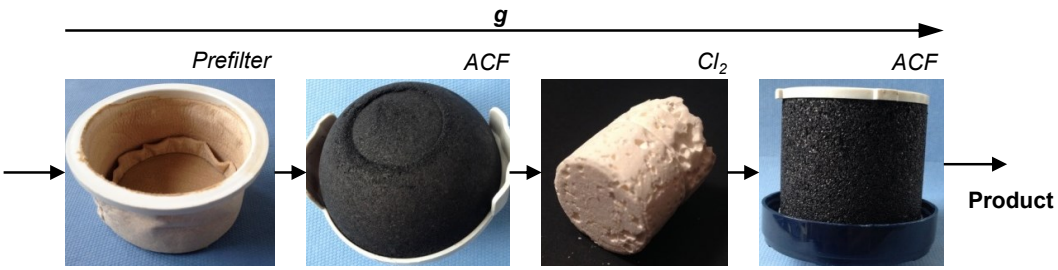

Fig. 3. Schematic of chlorine-based system C including pre-filter, ACF and chlorine dosage (Cl_2).

was determined volumetrically with a flask and timer. The DOC was evaluated with a TOC–TNb Analyzer (DIMATOC® 2000) according to DIN EN 1484. The specific absorption coefficients (SAC) were measured as absorbance E at path length d = 10 mm and wavelengths of 254 and 436 nm with a Kontron UVIKON 922 double beam spectrometer and Thermo Fisher Genesys 20 Vis spectrometer, respectively: $SAC(\lambda) = E(\lambda)/d$. The SAC254 (also known as UV254) is a measure for aromaticity (indicating C–C double bonds and thus organic compounds such as humic acids) while SAC436 is a measure of the color of the sample. Free chlorine determination was performed with Hach LCK310 cuvette tests (Hach Lange, Germany). The microbe concentrations in the overnight culture and spiking liquids were determined by optical density using a Thermo Fisher Genesys 20 Vis spectrometer (λ = 600 nm) which was previously calibrated with serial dilution. The *E. coli* samples were analyzed with dilutions on agar plates in duplicate after 20 h of incubation at 37°C (DSMZ medium 1) [23]. Additionally, to improve the detection limit in the product water, the presence/absence of *E. coli*

Table 1
Feedwater characteristics set values

Test phase	General	Challenge
Turbidity (NTU)	<1	50
DOC (mg/L)	<3	10
TDS (mg/L)	<500	1,500
pH	7	9
E. coli (cfu/mL)	10^5	10^5
MS2 (pfu/mL)	2×10^4	2×10^4
Production rate (L/d)	30	30
Temperature (°C)	20	10

in 100 mL sample was determined according to [24]. The MS2 phage samples were also quantified using serial dilution in duplicate after 20 h at 37°C as plaques on agar plates (host *E. coli* DSM-5695, DSMZ medium 544) [19,23].

3. Results and discussion

3.1. Production rates

In the general phase, constant production rates for all systems were evident: 22 ± 1 L/h for system A, 6 ± 2 L/h for system B and 5 ± 1 L/h for system C. The production rate of systems A and C was within or above the nominal value given by the manufacturer whereas production rate of system B was below 18.6 L/h and exhibited a slight decline with tap water which was reversible with recommended cleaning procedure (day 5 in Fig. 4).

During the challenge phase with high contents of suspended solids, the production rate of the membrane-based systems decreased drastically. As a consequence for the multi-stage purifier, the internal control switched off the pump as it failed to produce water with targeted UF/RO mixing ratio after approximately 50–100 L (steep flow rate decline in Fig. 4). Only the production rate of the chlorine-based purifier could be maintained using the recommended cleaning procedure requiring approximately 2–5 L of purified water (day 12 in Fig. 4). On the contrary, a cleaning procedure consisting of a manual backwash with 50 mL syringe was unable to restore system B's production rate (day 9 and 12 in Fig. 4).

3.2. Physicochemical parameters reduction

The analysis of physicochemical parameters was limited to the challenge phase (due to low levels in general phase feedwater). The multi-stage purifier (system A) reduced all parameters except conductivity to ≥89% (Fig. 5). Both membrane-based systems retained turbidity to 99.7% ± 0.2% due to their physical barrier. Organic indicators were partly reduced (system B: 33%–59%, system C: 26%–36%). However, system C showed only partial turbidity reduction (68% ± 20%) since it lacks a physical barrier. The top and bottom activated carbon filters had particle sizes of 0.2–0.3 and 1–2 mm, respectively (analyzed by scanning electron microscopy [SEM],

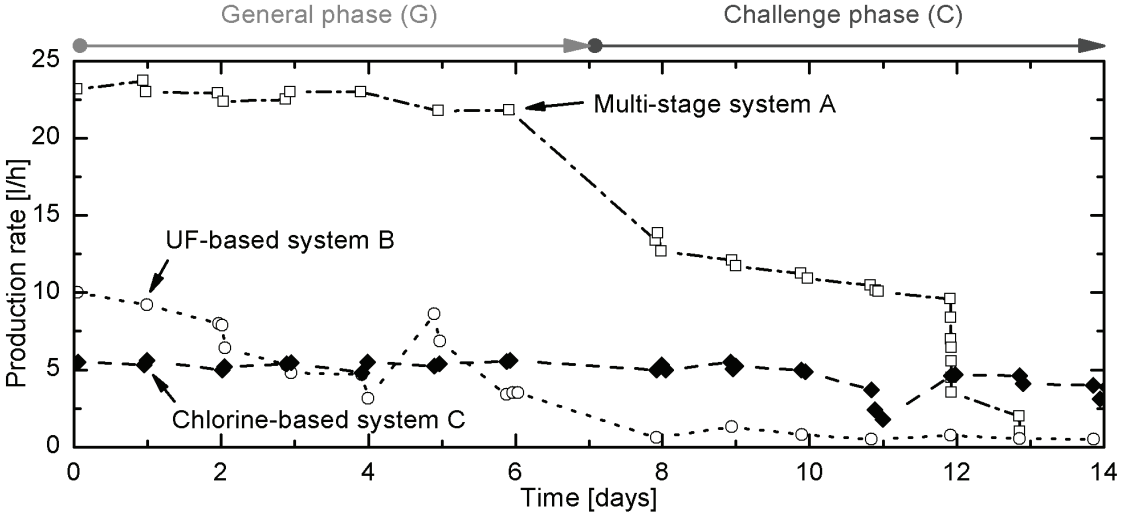

Fig. 4. Production rates of the investigated systems (second run, feedwater according to Table 1).

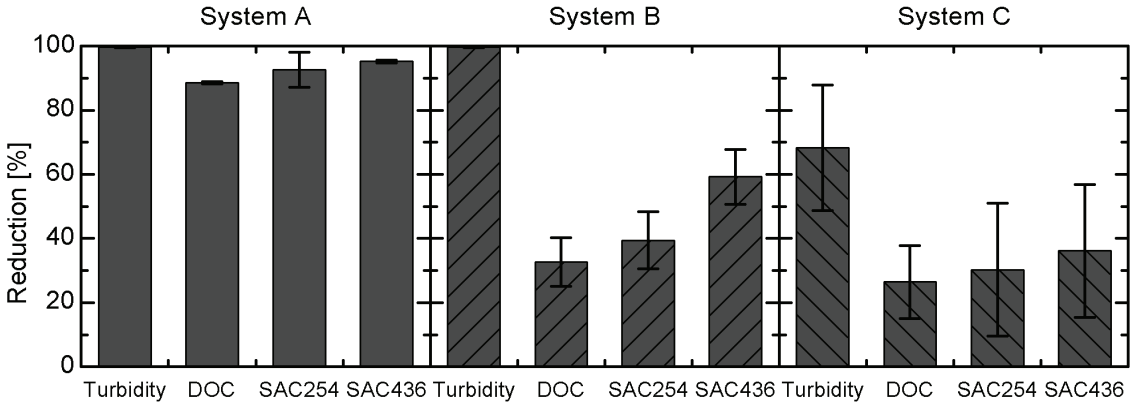

Fig. 5. Reduction of physicochemical parameters during challenge phase by multi-stage system A (left, n = 5–9), UF-based system B (center, n = 3–7) and chlorine-based system C (right, n = 7–14); mean values ± standard deviations.

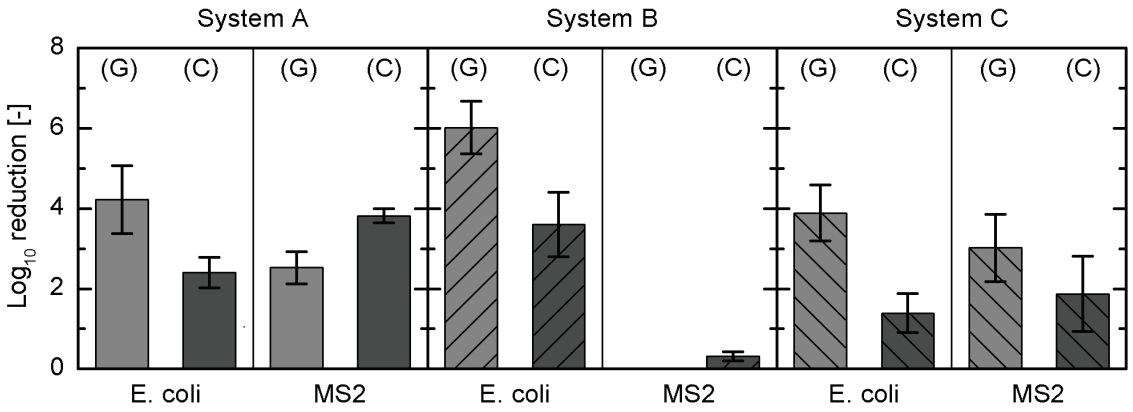

Fig. 6. Bacteria (*E. coli*) and virus (MS2 phage) $\log_{10}$ reduction (LRV) by multi-stage system A (left), UF-based system B (center) and chlorine-based system C (right); mean values ± 95% confidence intervals (in general phase (G) and challenge phase (C), n = 7–11). In the general phase (G), all systems were "highly protective against bacteria". Systems A and C can be expected to be "protective against viruses".

Fig. 7). The selective "pore size" is thus expected to be 20 μm or larger. 60 and 90 wt% of used fine dust particles are smaller than 11 and 44 μm, respectively (manufacturer's information), explaining the partial turbidity reduction.

Conductivity was reduced considerably only by the multi-stage system A depending on the chosen settings. Purified water ranged from 150 to 640 μS/cm in all cases (TDS ≤ 400 mg/L). The measured salt retention agreed well with manufacturer's information about the RO membrane (~90% TDS reduction). The feedwater salt level affected the default settings for operational mode which resulted in mixing ratios between UF and RO train of approximately 50:50 in the general phase and 7:93 in the challenge phase, respectively. These operational modes yielded total salt retention of 44% ± 12% and 85% ± 4% in the general and the challenge phase, respectively. In addition, the total water recovery decreased from ~45% in the general phase to ~25% in the challenge phase because the share treated by RO train (with cross-flow operation compared with dead-end operated UF stage) increased. Retentate was simply discharged in all cases.

3.3. Microbial reduction

3.3.1. Bacteria and viruses

E. coli and MS2 phages were chosen as indicator organisms for bacteria and viruses, respectively. In the general phase (resembling the normal operation mode of the household purifiers), the $\log_{10}$ reduction values (given as mean value ± 95% confidence interval) for *E. coli* and MS2 phages were 4.2 ± 0.8 and 2.5 ± 0.4 (system A), 6.0 ± 0.7 and –0.1 ± 0.2 (system B) and 3.9 ± 0.7 and 3.0 ± 0.8 (system C), respectively (Fig. 6). The UF-based system B was not able to retain MS2 phages, which is in agreement with the membrane pore size of ≥0.1 μm identified by SEM (Fig. 7). Hence, all systems can be considered as "highly protective against bacteria" [18], but only system C as "protective against viruses" (Table 2). System A may be "protective against viruses" as well.

In the challenge phase, *E. coli* reduction decreased by about 2 $\log_{10}$ units for all systems which may be explained by additional chlorine consumption by organics and suspended matter for system C [25] and by increased bacteria passage through the employed membranes for the two other systems. A possible reason for the latter fact is partial membrane deterioration caused by the increased particle load. The MS2 reduction increased for membrane-based systems in the challenge phase which can be attributed to phage adsorption onto suspended particles or a built-up particle cake layer (screening the phages) whereas it decreased slightly for system C due to increased chlorine consumption by organics and suspended matter. The slowly dissolving chlorine compound contained ~10% of 1,3-dichloro-5,5-dimethylhydantoin (DCDMH) [26] identified by fourier transform infrared (FTIR) spectroscopy[2] (Fig. 8). During normal operation conditions (general phase), it caused a slight pH increase from 7.7 ± 0.1 to 8.1 ± 0.5. DCDMH yields hypochlorous acid in aqueous solutions that causes disinfection. Free chlorine level directly after the dosage unit ranged from approximately 1 to 2 mg/L and depleted to around 0.2 mg/L after 1 h and was below detection limit (0.05 mg/L) on the following day (Fig. 9).

The microbial reduction of system A can be attributed to multiple barriers: pre-treatment (not measured – negligible reduction expected), UF stage (approximately 2–3 and approximately 0–3 $\log_{10}$ reduction for *E. coli* and MS2, respectively), RO stage (approximately 3–6 and approximately 1–3 $\log_{10}$ reduction for *E. coli* and MS2, respectively) – resulting in a UF/RO mixed stage reduction (approximately 2–3 and approximately 0–1 $\log_{10}$ reduction for *E. coli* and MS2, respectively) – and post-treatment comprising granular activated carbon (GAC) and UV (approximately 0–2 and ~3 $\log_{10}$ reduction for *E. coli* and MS2, respectively). All single stage reductions are calculated from limited amount of samples and are thus just indicative. The RO stage exhibited as expected the highest $\log_{10}$ reduction from all single stages. In addition, post-treatment (with UV irradiation as dominating process) showed good reduction of MS2 phages which are relatively resistant to UV irradiation, and thus demonstrated its effectiveness. The germicidal UV dose

2 Percentage calculated by relative heights of the absorbance peaks at 1,730–1,760 cm^{-1} and 1,340 cm^{-1}.

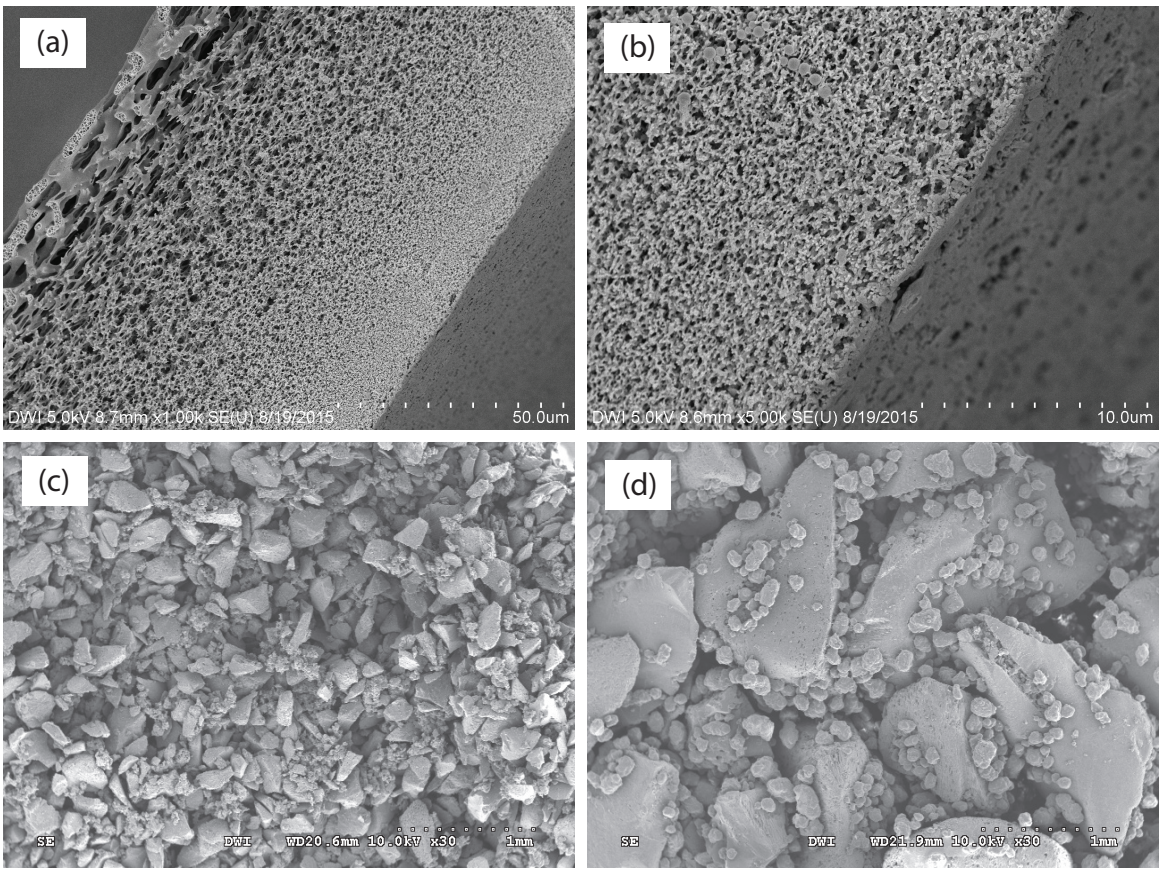

Fig. 7. Scanning electron micrographs of UF membrane of system B ((a) – 1,000×, (b) – 5,000×) and activated carbon filters of system C ((c) – first filter (30×), (d) – second filter (30×)).

Table 2
Performance targets for household drinking water purifiers [18]

Pathogen class	Required $\log_{10}$ reduction		
	Interim	Protective	Highly protective
Bacteria	Achieves "protective" target for two classes of pathogens and results in health gains	≥2	≥4
Viruses		≥3	≥5
Protozoa		≥2	≥4

D_{UV} of the installed 4 W low-pressure mercury lamp can be calculated as:

$$D_{UV} \le P_{UV} \cdot \tau / A_{\text{reactor}} = 0.9\ W \cdot 7\text{s} / 75\ \text{cm}^2 = 84\ \text{mJ cm}^{-2} \quad (1)$$

where P_{UV}, τ and A_{reactor} are nominal UV radiation power output, hydraulic retention time and inner surface area of the UV reactor. Lamp aging can reduce the dose by up to 20% (bulb manufacturer information). Crittenden et al. [27] reported a required UV dose for 2 $\log_{10}$ reduction of at least 20–100 mJ/cm^2 which is assured in the present case under the assumption of negligible energy losses and under optimal water quality (perfect UV transmission in water).

3.3.2. Protozoa

The third pathogen class (protozoa) has not been investigated experimentally in this study. However, the membrane-based systems A and B allow an estimation of protozoa reduction governed by size exclusion based on bacteria reduction (*E. coli*: 0.3–0.5 μm × 1–2 μm) because naturally occurring relevant pathogenic cysts are larger in size (*Cryptosporidium parvum* oocysts: 3–5 μm, *Giardia lamblia* cysts: 11–14 μm long and 7–10 μm wide) [27]. The mean *E. coli* reduction was approximately 2–3 $\log_{10}$ for system A (calculated UF/RO mixed reduction) and ≥4 $\log_{10}$ for system B, respectively. Retention of larger pathogens can be expected at least as high and thus ≥2 $\log_{10}$. Hence, both membrane-based systems can be expected to be "protective against protozoa". No estimation for protozoa reduction by size exclusion is possible for chlorine-based system C. Taking the resistance against chlorine of *Cryptosporidium* oocysts into account, an estimation can be based on respective chlorine exposure (*C*–*t* values) supposing an exponential decrease of free chlorine concentration and using experimental data from the challenge phase (Fig. 9; deionized data for comparison). Exposure time equaled hydraulic residence time in the middle tank (~2 L), the bottom dwell tank (~3 L) and the storage tank (5 L) based on a constant flow rate of 5 L/h. The resulting *C*–*t* value ranged from 52 mg·min/L (2 h minimal exposure time) to 64 mg·min/L (infinite exposure time).

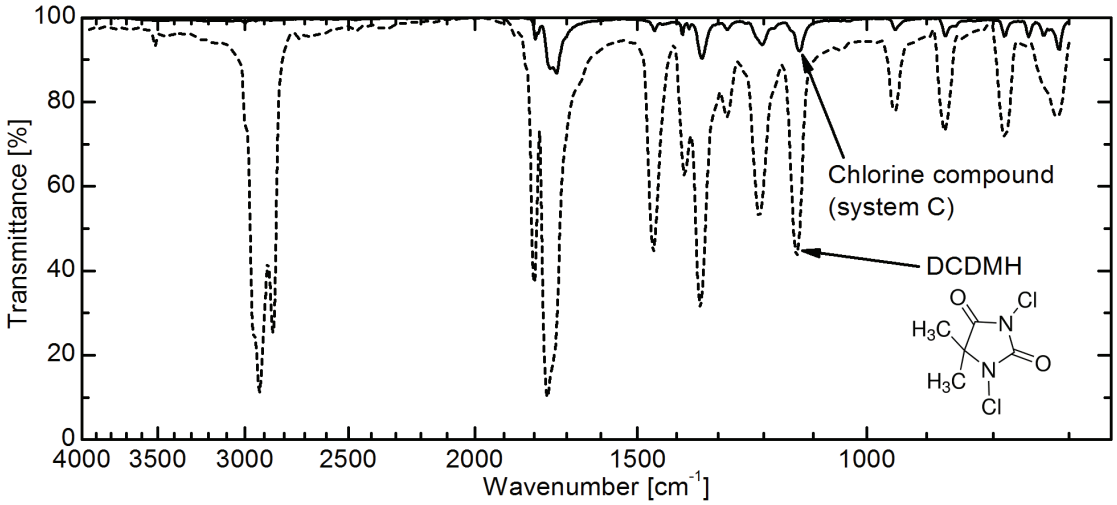

Fig. 8. FTIR spectra of chlorine compound of system C and 1,3-dichloro-5,5-dimethylhydantoin (DCDMH) [26].

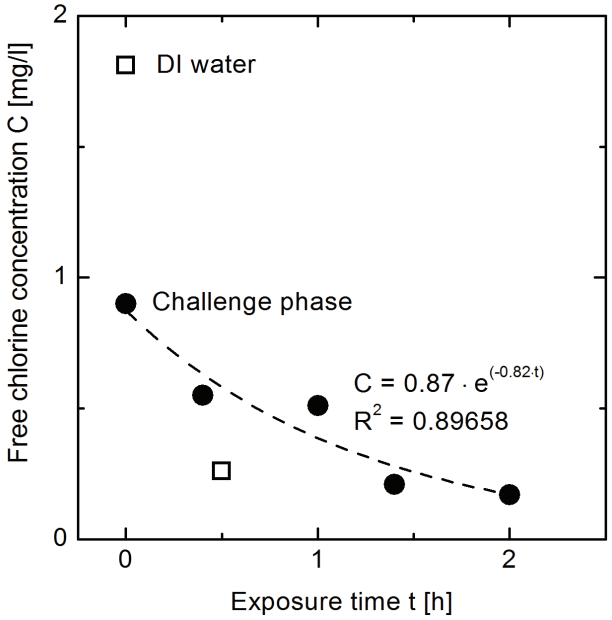

Fig. 9. Chlorine exposure estimation based on challenge phase for system C. Resulting *C–t* values ranged from 0.86 to 1.1 ppm·h in case of hydraulic retention time (2 h) and infinite exposure time, respectively.

This *C–t* value assures >2 $\log_{10}$ reduction for bacteria (*E. coli*, *Legionella pneumophila*), protozoa (*G. lamblia*) and viruses (*Adenovirus, Calicivirus*) [27] which was also demonstrated for *E. coli* and MS2 phages in this study. However, 2 $\log_{10}$ reduction of *Cryptosporidium* oocysts would require a *C–t* value of ~2,000 mg·min/L. Hence, system C is not expected to be "protective against (all) protozoa".

Comparing the microbial reduction results in this study with a study by WHO [28] that includes microbial reduction results under similar conditions for similar technologies, such as UF, chlorine and UV disinfection, it can be seen that in general the results show same trends and are well comparable. Reported reductions by successfully tested technologies in [28] are higher than in this study. UF technology in [28] is somewhat superior to what was measured in the present study for bacteria (5–7 $\log_{10}$ vs. 2–6 $\log_{10}$). However, the so-called "UF" unit in the present study must rather be seen as microfiltration than UF because it does not retain viruses. This is in accordance with [12] reporting mean reduction of 6.9 $\log_{10}$ for *E. coli* and 4.7 $\log_{10}$ for MS2, respectively, for a different UF-based purifier. Chlorine disinfection in [28] performed better than in this study for bacteria (6 $\log_{10}$ vs. 4 $\log_{10}$) and viruses (4 $\log_{10}$ vs. 3 $\log_{10}$). This could be due to higher chlorine dosage. UV disinfection in [28] probably performed better than the UV lamp of the multi-stage purifier in this study (calculated from limited amount of samples) for bacteria (6 $\log_{10}$ vs. 0–2 $\log_{10}$) and viruses (4 $\log_{10}$ vs. ~3 $\log_{10}$). The reduction of *E. coli* and MS2 by traditional biosand filtration is expected to be lower and definitely more variable over time due to filter ripening (0.3–4 $\log_{10}$ *E. coli* and 0–1.3 $\log_{10}$ MS2) compared with chlorination with low organic loading and membrane filtration in general [13].

3.4. Maintenance, service and costs

All commercial household purifiers need regular replacement of certain parts. Respective intervals range from about 2 months (GAC cartridges and chlorine dosage unit) to 2 years (UV lamp) assuming daily family use of the purifier. For continuous system operation it is hence of importance that servicing is available locally and within short response time to supply spare parts and to provide qualified technical support. Some system units include automatic shutdown if the design lifetime of single parts is exceeded (i.e., chlorine dosage unit of system C, UV lamp of system A), thus preventing users from consuming unsafe water. Other system units do not include such safety features (i.e., membrane failure/damage for systems A and B). The after sales service of manufacturers varies and concentrates on big cities. Rural areas are almost not covered due to difficult accessibility and the absence of skilled servicemen. Various studies highlighted the importance of simplicity in operation and maintenance to safeguard

Table 3
Annualized cost of selected household water treatment systems

	Multi-stage purifier (A)	UF-based purifier (B)	Chlorine-based purifier (C)
Capital annuity cost	68.63 EUR p.a.	9.80 EUR p.a.	5.52 EUR p.a.
	5,121.46 INR p.a.	731.67 INR p.a.	412.18 INR p.a.
Annual replacement cost	32.66–85.01 EUR p.a.	21.78–50.43 EUR p.a.	63.09 EUR p.a.
	2,437.50–6,344.00 INR p.a.	1,625.60–3,763.20 INR p.a.	4,708.00 INR p.a.
Total annuity cost	101.29–153.64 EUR p.a.	31.59–60.23 EUR p.a.	68.61 EUR p.a.
	7,558.96–11,465.46 INR p.a.	2,357.27–4,494.87 INR p.a.	5,120.18 INR p.a.
Specific water cost	9.25–14.03 EUR/m^3	2.88–5.50 EUR/m^3	6.27 EUR/m^3
	690.32–1,047.07 INR/m^3	215.28–410.49 INR/m^3	467.60 INR/m^3

Assumptions: interest rate of 7% p.a., lifetime of 5 years, no residual value, currency exchange 0.0134 EUR = 1 INR (July 2016), water consumption of four-person household equaling 30 L/d.
System A: UV bulb costs about 250 INR (11 W) and needs to be replaced 0 (5,000 h × 15 L/h) to 3.38 (operation 12 h/d) times in 5 years. All filter/membrane spare parts cost between 1,500 and 3,800 INR, replaced 8.125 times in 5 years [30,31].
System B: Replacement kit costs 640 INR and needs replacement every 1,800 L (29.4 times/5 years) to 4,000 L (12.7 times/5 years) [32].
System C: Replacement kit costs 550 INR (plus 50 INR for delivery and installation which have been neglected) every 1,250 L (42.8 times/5 years) (manufacturer information).

stable and long-term performance of household systems [8,10,11,14,29]. Field testing would be required to evaluate the question of long-term performance of these purifiers in rural settings in detail but it was out of scope of the present study. The user is expected to perform system maintenance which was explained as text and picture for all considered purifiers (English version, additional local language version (Hindi) in case of the tested offline purifiers). The cleaning steps for the systems B and C were considered feasible, but required basic hygienic and technical knowledge. System A performed automatic flushing. No manual cleaning was foreseen. The cost estimation for specific water cost is based on manufacturer information and online prices for spare parts required for regular replacement (Table 3). Both offline purifiers yield specific cost of <7 EUR/m^3 whereas the multi-stage purifier costs 9–14 EUR/m^3 mainly due to higher investment cost. Annual replacement cost is in the same range for the different systems, but varies with replacement intervals highlighting the advantage of long-lasting components. All household water treatment systems are significantly less expensive than buying drinking water in 20 L jars costing about 50–80 INR in Mumbai (July 2016) translating to about 34–54 EUR/m^3 (2,500–4,000 INR/m^3).

3.5. Miscellaneous

Latest generation multi-stage purifiers come with a slightly different configuration: UF and RO stage are no longer constituted in parallel trains but in serial stages providing an additional safety barrier. Hence, these purifiers also include an additional remineralization stage (limestone filtration) as all product water passes RO stage.

In case the suspended solid content of the feedwater is as high as in the challenge phase, a pre-treatment by, i.e., sedimentation or pre-filtration is recommended to protect all the systems. Since membrane fouling is attributed mainly to inorganic particles, simple cloth (nylon or sari folded four times) pre-filtration is able to completely remove particles >20 μm [33].

4. Conclusions

The water produced by the studied systems varied in quality and production rates depending on the employed technologies and driving forces (electricity vs. gravity). All systems were able to provide satisfactory disinfection against bacteria (*E. coli*) when applied for the intended use (represented by spiked tap water). However, MS2 phage reduction varied among the different systems and was generally below *E. coli* reduction. For disinfection only, gravity-driven systems represented cheap and effective solutions. For sophisticated reduction of physicochemical parameters a physical barrier is required which can be further improved by multi-stage treatment trains. RO is only required for salinity reduction. Hence, when selecting a household water purifier the available raw water quality has to be taken into account. However, none of the tested household purifiers was able to maintain drinking water production when using it for treating turbid river water with a turbidity of 50 NTU which can occur in typical rural settings in India. In this case, the membrane-based systems did not meet the target production quantity and the chlorine-based system did not meet the target product water quality. Hence, there is no commercial solution available to produce drinking water from turbid water (i.e., river) at household level. In order to provide a respective solution, the need for proper pre-treatment and reliable membrane filtration (microfiltration or UF) including effective cleaning after severe fouling was identified. In addition, a mandatory standardized testing and certification of household water purifiers is suggested including a detailed specification of usage conditions.

Acknowledgments

This work was supported by the European Commission (7th Framework Programme, Project Water4India, grant no. 308496). The authors acknowledge Tino Schlepütz, Andreas Nessel and Karin Faensen from RWTH Aachen University for supporting the experimental study and conducting scanning electron microscopy, respectively. Walter Tillmann from DWI Leibniz Institute for Interactive Materials is acknowledged for FTIR analysis.

References

[1] M.T. Boot, S. Cairncross, Eds., Actions Speak: The Study of Hygiene Behaviour in Water and Sanitation Projects, IRC International Water and Sanitation Centre, The Hague, and London School of Hygiene and Tropical Medicine, London, 1993.
[2] M.A. Shannon, P.W. Bohn, M. Elimelech, J.G. Georgiadis, B.J. Mariñas, A.M. Mayes, Science and technology for water purification in the coming decades, Nature, 452 (2008) 301–310.
[3] Census India, 2011. Available at: http://www.censusindia.gov.in/2011census/hlo/hlo_highlights.html (Accessed 1 July 2016).
[4] TV Veopar Journal, http://www.tvj.co.in/, April 2012, online issue.
[5] T. Gross, L. Breitenmoser, C. Hugi, B. Aumeier, A. Bello-Dambatta, E. Cadena, H. Chikurel, P. Cruddas, S. Sadr, Y. Sheva, Application of Framework for Selected Region – Karnataka State and the Example Community Bhadravati, EU Project Water4India (308496), 7th Framework Programme, Deliverable 2.2, 2014.
[6] E. Mintz, F. Reiff, R. Tauxe, Safe water treatment and storage in the home: a practical new strategy to prevent waterborne disease, J. Am. Med. Assoc., 273 (1995) 948–953.
[7] R.E. Quick, L.V. Venczel, E.D. Mintz, L. Soleto, J. Aparicio, M. Gironaz, L. Hutwagner, K. Greene, C. Bopp, K. Maloney, D. Chavez, M. Sobsey, R.V. Tauxe, Diarrhoea prevention in Bolivia through point-of-use water treatment and safe storage: a promising new strategy, Epidemiol. Infect., 122 (1999) 83–90.
[8] M.D. Sobsey, Managing Water in the Home: Accelerated Health Gains from Improved Water Supply, World Health Organization, Department of Protection of the Human Environment, Geneva, 2002.
[9] J. Wright, S. Gundry, R. Conroy, Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use, Trop. Med. Int. Health, 9 (2004) 106–117.
[10] T. Clasen, L. Haller, D. Walker, J. Bertram, S. Cairncross, Cost-effectiveness of water quality interventions for preventing diarrhoeal disease in developing countries, J. Water Health, 4 (2007) 599–608.
[11] M.D. Sobsey, C.E. Stauber, L.M. Casanova, J.M. Brown, M.A. Elliott, Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world, Environ. Sci. Technol., 42 (2008) 4261–4267.
[12] T. Clasen, J. Naranjo, D. Frauchiger, C. Gerba, Laboratory assessment of a gravity-fed ultrafiltration water treatment device designed for household use in low-income settings, Am. J. Trop. Med. Hyg., 80 (2009) 819–823.
[13] M.A. Elliott, C.E. Stauber, F. Koksal, F.A. DiGiano, M.D. Sobsey, Reductions of *E. coli*, echovirus type 12 and bacteriophages in an intermittently operated household-scale slow sand filter, Water Res., 42 (2008) 2662–2670.
[14] M. Peter-Varbanets, C. Zurbrügg, C. Swartz, W. Pronk, Decentralized systems for potable water and the potential of membrane technology, Water Res., 43 (2009) 245–265.
[15] Dr. Sandhya Shrivastava, Head of Bhavan's Research Center (Microbiology), laboratory certified by NSF P231, Mumbai, personal communication, April 2016.
[16] Mrs. Rajul Parikh, President of Water Quality India Association, Mumbai, personal communication, April 2016.
[17] Unites States Environmental Protection Agency (US EPA), Guide Standard and Protocol for Testing Microbiological Water Purifiers, 1987.
[18] World Health Organization (WHO), Evaluating Household Water Treatment Options, Health-Based Targets and Microbial Performance Specifications, WHO Press, Geneva, 2011.
[19] B. Aumeier, X. Jiang, S. Djeljadini, T. Schlepütz, S. Yüce, M. Wessling, Challenge Test of Indian Household Drinking Water Purifiers, M. Wessling, J. Pinnekamp, Eds., 11. Aachener Tagung Wassertechnologie, Aachen, 2015, pp. 387–397. Available at: https://gigamove.rz.rwth-aachen.de/d/id/ajxDV7DYndjgCw
[20] C. Ray, R. Jain, Low Cost Emergency Water Purification Technologies, Integrated Water Security Series, 1st ed., Butterworth-Heinemann, Waltham, 2014.
[21] DSMZ. Available at: https://www.dsmz.de/catalogues/details/culture/DSM-613.html?tx_dsmzresources_pi5%5BreturnPid%5D=304 (Accessed 10 May 2017).
[22] DSMZ. Available at: https://www.dsmz.de/catalogues/details/culture/DSM-13767.html?tx_dsmzresources_pi5%5BreturnPid%5D=304 (Accessed 10 May 2017).
[23] Unites States Environmental Protection Agency (US EPA), Method 1602: Male-specific (F^+) and Somatic Coliphage in Water by Single Agar Layer (SAL) Procedure, Washington, D.C., USA, 2001.
[24] European Committee for Standardization (CEN), Water Quality – Enumeration of *Escherichia coli* and Coliform Bacteria – Part 1: Membrane Filtration Method for Waters with Low Bacterial Background Flora (ISO 9308–1:2014), Brussels, Belgium, 2014.
[25] H. Mohamed, J. Brown, R.M. Njee, T. Clasen, H.M. Malebo, S. Mbuligwe, Point-of-use chlorination of turbid water: results from a field study in Tanzania, J. Water Health, 13 (2015) 544–552.
[26] Sigma-Aldrich. Available at: http://www.sigmaaldrich.com/spectra/ftir/FTIR003364.PDF (Accessed 10 May 2017).
[27] J.C. Crittenden, R.R. Trussell, D.W. Hand, K.J. Howe, G. Tchobanoglous, MWH's Water Treatment, Principles and Design, 3rd ed., John Wiley & Sons, Hoboken, 2012.
[28] World Health Organization (WHO), Results of Round 1 of the WHO International Scheme to Evaluate Household Water Treatment Technologies, WHO Press, Geneva, 2016.
[29] H. Mohamed, T. Clasen, R.M. Njee, H.M. Malebo, S. Mbuligwe, J. Brown, Microbiological effectiveness of household water treatment technologies under field use conditions in rural Tanzania, Trop. Med. Int. Health, 21 (2016) 33–40.
[30] Amazon. Available at: http://www.amazon.in/Philips-Lamp-other-Water-Purifiers/dp/B01FFWQXB2/ref=pd_sim_sbs_23_2?ie=UTF8&dpID=21TS1wdPthL&dpSrc=sims&preST=_AC_UL160_SR160%2C160_&psc=1&refRID=0VQSNJX1YMHAGD7YKDBH (Accessed 10 May 2017).
[31] Amazon. Available at: http://www.amazon.in/dp/B01C1VWTJU?psc=1 (Accessed 10 May 2017).
[32] Amazon. Available at: http://www.amazon.in/Kent-Gold-Optima-Spare-Kit/dp/B00SMFPJG0 (Accessed 10 May 2017).
[33] R.R. Colwell, A. Huq, M. Sirajul Islam, K.M.A. Aziz, M. Yunus, N. Huda Khan, A. Mahmud, R. Bradley Sack, G.B. Nair, J. Chakraborty, D.A. Sack, E. Russek-Cohen, Reduction of cholera in Bangladeshi villages by simple filtration, Proc. Natl. Acad. Sci. USA, 100 (2003) 1051–1055.