Microbiological performance of novel household water treatment devices in India

Z. P. Bhathena, S. Shrivastava, Poonam Londhe and Joe Brown

ABSTRACT

Commercial innovation of household-scale water treatment (HWT) devices is rapid in India, where unsafe drinking water contributes to the high burden of disease and death associated with diarrhoeal diseases. Performance testing data for novel devices are not publicly available and there has been no systematic attempt to independently verify manufacturer effectiveness claims. We purchased three gravity-driven HWT devices available on the Indian market to evaluate their performance in reducing bacteria, viruses, and protozoan surrogates in the laboratory according to World Health Organization testing protocols. Results indicated that technologies were moderately effective in reducing *Escherichia coli* (1.6–2.9 $\log_{10}$) and MS2 (1.4–2.8 $\log_{10}$), and less effective against *Bacillus subtilis* spores (0.73–2.2 $\log_{10}$) and 3 μm microspheres (0.33–0.56 $\log_{10}$), as means over the testing period (750–4,000 l). Effectiveness declined sharply over the duration of testing for each device, suggesting that the manufacturer-specified effective lifespans were overestimated for all devices. Moderate variability was observed across challenge conditions intended to represent actual use conditions, but performance was not significantly different between challenge waters or ambient testing temperature. Our results suggest that these novel devices do not meet international minimum performance recommendations and that manufacturer effectiveness claims are misleading. Further technological innovation and regulation in this sector may serve to protect public health.

Key words | drinking water, hygiene, performance testing, water purifiers

Z. P. Bhathena (corresponding author)
S. Shrivastava
Poonam Londhe
Dept of Microbiology,
Bhavans Research Centre,
Bhavans College, Andheri,
Mumbai 58,
India
E-mail: *zarine_bhathena@rediffmail.com*

Joe Brown
Georgia Institute of Technology,
School of Civil and Environmental Engineering,
790 Atlantic Drive,
Atlanta, GA 30332-0355,
USA

INTRODUCTION

An estimated 97 million people in India lack access to an 'improved' water source (WHO/UNICEF 2012), and many more may rely on microbiologically or chemically unsafe water since 'improved' does not always equal 'safe' (WHO 2011a; Onda *et al.* 2012). Only 23% of the total population is served by a household-level piped water connection. Connected households in India may experience frequently intermittent service, which is a risk factor for microbial contamination. The remaining 77% rely on surface water, private or public wells, rainwater harvesting, or other sources. While water supplies may often be low-risk at the point of treatment or distribution, any drinking water collected outside the home is at high risk of microbial contamination by the time it is ultimately consumed, due to possible re-contamination in transport, storage, and handling (Wright *et al.* 2004). Because the quality of drinking water may not be trusted, household water treatment (especially boiling) is common in India (Clasen *et al.* 2008), even in households that are connected to a piped water supply. Poor access to safe water is in part responsible for high childhood mortality due to diarrhoea in India, which has been estimated by various methods to be as few as 212,000 (Liu *et al.* 2012) or up to 535,000 (Boschi-Pinto *et al.* 2008) deaths per year. India has more deaths due to diarrhoea in children than any other country (ibid.; WHO Global Health Observatory 2008).

Because universal, safe, reliable, on-plot water supply may be years away for most Indians, household-level water treatment (HWT) may help increase access to safer drinking

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water (Mintz *et al.* 1995; Sobsey 2002; WHO 2007). A wide variety of household-level water treatment devices are now available in the Indian market, mostly aimed at middle to upper-income consumers in urban areas (Brown *et al.* 2009). Despite increasing sales and growth in the Indian water treatment device market, few technologies have been subjected to laboratory testing to verify manufacturers' claims of microbiological effectiveness, so their role in increasing access to safe water in India remains unknown.

In this paper, we describe systematic testing of three widely available, gravity-driven, household-scale drinking water filtration devices on the Indian market. Our objective in undertaking this research was to evaluate the performance of the devices for their ability to remove microbes from water over long-term daily use, under realistic use conditions, and in accordance with recently published guidance and recommendations for microbial performance testing by the World Health Organization (WHO 2011b). A secondary aim of our study was to assess whether chemical leachate from filtration devices could result in any health risks, which has been suggested previously (Brown *et al.* 2012). The microbiological performance and chemical leachate data that we have produced is a necessary first step in a broader assessment of the potential current and future roles these previously uncharacterized devices may play in providing safer drinking water in India.

MATERIALS AND METHODS

Devices

We purchased three filtration devices (Table 1) for testing. From an informal survey of Mumbai retail outlets stocking HWT products, these models were most common apart from the Hindustan Unilever Pureit device, which has previously been tested in a similar manner (Clasen *et al.* 2006). Each device varied by treatment mechanism, design life, flow rate, and effectiveness claims. Devices required no electricity or pressurized water input (operating by gravity only), no chemical dosing by the user, and included integrated safe storage of treated water up to 18–20 L. Units were designed to operate as 'table top' filters, rather than plumbed-in devices such as point-of-entry (POE) or under-sink technologies.

Testing procedure

We used current WHO (2011b) performance testing recommendations in developing laboratory methods. The 12 devices (four of each) were assembled according to manufacturers' instructions. The devices were monitored for their performance throughout their recommended lifespan (Table 1), with 24 L of microbe-spiked challenge water (Table 2) dosed per day manually. Challenge water was prepared daily from a stock solution of microbial cultures at each spike point, with simultaneous bacteria and virus spikes

Table 1 | Devices tested, reported mechanisms, and recommended lifespan

Device name and retail cost in Mumbai (2011)	Reported active mechanism	Manufacturer recommended design life	Flow rate (ml/min)	Treated water storage volume (litres)	Claims
Tata Swatch (Rs 1195)	Granular media filtration and inactivation via contact with silver nanoparticles	3,000 l	20–100	18 L	99.99% reduction of bacteria and viruses from water
Kent Gold (Rs 2495)	Hydrophilic ultrafiltration membrane encased within a hollow fibre tube, sediment filter for removal of suspended impurities, activated carbon filter augmented with silver nanoparticles	4,000 l	20–130	20 L	'Healthier water'. NSF certified cyst reduction
Aquasure PCTi (Rs 2290)	'*Positively charged attractors*' that trap microbes. Proprietary 'microfibre mesh' employing nanotechnology.	750 l	20–45	20 L	Removes 'all' disease causing bacteria, viruses, and cysts

Table 2 | Characteristics of challenge water

Parameters	Challenge water 1	Challenge water 2
Source	Packaged mineral water	Packaged mineral water seeded with autoclaved 1% untreated sewage
Chlorine, mg/l	<0.01	<0.01
pH, range (mean)	7.0–8.0 (7.5)	7.0–8.5 (7.5)
Turbidity, NTU, range	<1–5	31–40
Temperature, range (mean)	28–33 °C (30.5 °C)	18–23 °C (20 °C)
Total suspended solids (TSS), mean	2	3.6
Total organic carbon (TOC), mg/l	< 0.01	0.01–0.02

on the first day and spores and microspheres the second. New stock cultures were prepared once per week and stored at 4 °C. Filters were cleaned when needed to restore flow rate, according to manufacturers' instructions. Samples of untreated and treated water were assayed for test microbes and a comparison of concentrations in pre- and post-treatment water was used to determine the $\log_{10}$ reduction of test microbes.

To obtain representative microbial performance data from devices, log reduction values were determined at 0, 25, 50, 60, 75 and 100% of the manufacturer-recommended life spans of the devices, consistent with WHO (2011b) recommendations. At these sample points, we collected the first 500 ml of throughput for analysis. Because the Tata Swatch device employed silver-augmented granular media requiring extended contact time to achieve optimal performance, we tested samples from this device as the first 500 ml throughput and additionally after 3 hours of contact time attained by blocking the outlet such that the input water collected in the chamber and was effectively in contact with the germicidal agent for 3 hours, after which the outlet was released and water collected for analysis.

Challenge waters

Two types of test waters were used in challenge tests, consistent with WHO (2011b) recommendations: (1) packaged mineral water to model high quality water with low dissolved matter; and (2) packaged mineral water seeded with 1% (v/v) sterilized untreated wastewater to represent poor quality of water with high organic load (Table 2). Test waters were seeded with known concentrations of bacteriophage, bacteria, and surrogates for protozoan parasites. The test microbes and surrogates were chosen based on WHO (2011b) recommendations and were used as surrogates for pathogenic bacteria, viruses, and protozoa potentially found in untreated drinking water. The bacterial group was represented by *Escherichia coli* ATCC 10536 and was spiked into the input water at a concentration of 10^6 cfu/ml. The viral group was represented by male-specific coliphage MS2 ATCC 15997, spiked at a concentration of 10^5 pfu/ml in input water. The protozoan group was represented by 3 μm microspheres (Fluroesbrite Plain YG 3.0 μm microspheres, Polysciences Inc., PA, USA), this would conservatively estimate removal by size-exclusion for protozoa (e.g., *Cryptosporidium* oocysts are 4–6 μm). *Bacillus* spp. spores have been suggested as experimental surrogates for *Cryptosporidium* oocysts in treatment process and transport modelling (Dey 1998; Nieminski *et al.* 2000; Chauret 2001; Verhille *et al.* 2003; WHO 2011b). We spiked *Bacillus subtilis* ATCC 6633 spores into the input water at a concentration of 10^4 cfu/ml, as we did not know whether the technologies would remove oocyst-sized particles by size exclusion only.

Microbiological analysis

E. coli ATCC 10536 was grown overnight, washed with phosphate-buffered saline (PBS), and adjusted to a culture density of 0.1 OD at 620 nm corresponding to approximately 10^8 cfu/ml. 1 ml of this culture suspension was added per litre of test water to attain a final concentration of 10^7 cfu/100 ml. *E. coli* were enumerated in pre- and post-filtration samples by filtering 100 ml of sample through 47-mm diameter, 0.45 μm pore size cellulose ester filters using a membrane filtration apparatus (USEPA 2002), followed by incubation on Endo agar. Plates were incubated at 37 °C for 18–24 h and *E. coli* concentrations expressed as colony forming units (cfu) per 100 ml of water.

MS2 bacteriophage suspensions were cultivated to obtain high-titre stocks (10^{14} pfu/ml). Phages were harvested

and spiked into challenge waters to concentrations of 10^5 pfu/ml. MS2 bacteriophages in pre- and post-treatment water were enumerated following the double agar layer (DAL) procedure (USEPA 1602). Plaques were counted and expressed as plaque forming units (pfu) per 100 ml.

B. subtilis spores were obtained by culturing *B. subtilis ATCC 6633* on sporulating agar (AK#2) for 5 days at 35 °C ± 2, with the culture aseptically scraped into 5 ml PBS and heated at 80 °C for 30 min (Dey 1998; Chauret 2001). Spore stock thus prepared and confirmed microscopically was spiked into challenge test water to achieve the concentration of 10^4 cfu/ml. Both pre- and post-treatment samples were pre-treated by heat exposure at 80 °C for 30 min before culturing on nutrient agar with 0.05% bromothymol blue by the pour plate method. The plates were incubated at 37 °C for 24 hours.

Microspheres were spiked into test waters to a concentration of 10^4 cfu/ml. 5 ml of pre- and post-treatment samples were filtered using 25 mm filters and individual microspheres were counted via epifluorescent microscopy and counts expressed as microspheres per 100 ml.

Physico-chemical parameters

Challenge test water samples used were analysed at every spike point for physico-chemical parameters like turbidity, total organic carbon, pH, and chlorine according to *Standard Methods* (Eaton *et al.* 2005). Post-treatment samples collected after every spike point challenge were analysed for turbidity and samples were collected and preserved for metals analysis (Al and Ag). Aluminium (Al) was assayed in pre- and post-treatment Aquasure PCTi device-treated water while silver (Ag) residue detection was performed on samples before and after passage through Tata Swatch and Kent Gold devices by ICP-OES (inductively coupled plasma–optical emission spectrophotometry (ThermoFisher Scientific Model: I-CAP 6300)).

Statistical methods

Log_{10} reduction values calculated from pre- and post-treatment assays were not normally distributed. We used the Mann–Whitney U test (Mann & Whitney 1947) and the Kruskal–Wallis one-way analysis of variance (Kruskal & Wallis 1952) to compare means across testing parameters (challenge water type, temperature) and for comparing device performance. Differences between groups were considered to be statistically significant at a significance level of $\alpha = 0.05$. All statistical testing was performed in Stata version 12.1 (StataCorp, College Station, TX, USA).

RESULTS

Results from microbial challenge testing are summarized in Table 3. Over the cumulative testing period per filter, all filters reduced *E. coli*, MS2, *B. subtilis* spores, and microspheres, although reductions declined over the recommended lifespans of the devices and moderate variability of challenge water type stored at varied temperatures. Figure 1 presents a summary of mean reductions collapsed across challenge conditions.

For the Tata Swatch device, mean reductions of *E. coli* across testing conditions were 1.6 $\log_{10}$ (range 0.10–7.1) and 2.6 $\log_{10}$ (range 0.10–7.4) after 3 hours of contact time before analysis. The devices were more effective against MS2, with mean reductions of 2.3 $\log_{10}$ (range 0.50–7.1) and 2.8 $\log_{10}$ (range 0.50–7.1) after 3 hours' contact time. *B. subtilis* spores were reduced by a mean of 0.83 $\log_{10}$ (range 0–3.1) and 0.73 $\log_{10}$ (range 0–3.5) after 3 hours. Microspheres were reduced minimally over the recommended device lifespan, by a mean 0.33 $\log_{10}$ (range 0.10–1.1) or 0.43 $\log_{10}$ (range 0.20–1.8) after contact time. Our hypothesis that greater contact time with silver-amended media would result in greater microbiological reductions was not supported by these data, however, as performances against *E. coli*, MS2, and spores were not significantly different between the two types of samples ($p = 0.25$, $p = 0.53$, $p = 0.66$, respectively).

The Kent Gold device reduced *E. coli* by a mean of 1.8 $\log_{10}$ (range 0.1–7.2), MS2 by a mean of 1.4 $\log_{10}$ (range 0–7.1), *B. subtilis* spores by 1.4 $\log_{10}$ (range 0–1.4), and microspheres by 0.49 $\log_{10}$ (range 0.20–1.8). The Aquasure PCTi device reduced *E. coli* by a mean of 2.9 $\log_{10}$ (range 0.80–7.4), MS2 by a mean of 2.1 $\log_{10}$ (range 0.50–7.1), *B. subtilis* spores by 2.2 $\log_{10}$ (range 0.10–6.8), and microspheres by 0.56 $\log_{10}$ (range 0.060–2.2). Reductions

Table 3 | Challenge effectiveness against test microbes (log reduction values) over defined lifespan

Spike point	*E. coli*				MS2				*B. subtilis* spores				3 μm Microspheres			
Mean temperature	30 °C		15–20 °C		30 °C		15–20 °C		30 °C		15–20 °C		30 °C		15–20 °C	
Challenge water	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Tata Swatch																
0%	2.0	2.7	2.0	0.8	7.1	7.0	7.1	7.0	2.0	2.4	2.4	3.1	1.0	1.1	0.9	0.9
25%	1.0	0.7	2.4	3.0	1.7	1.5	1.8	2.8	0.8	0.3	1.7	1.9	0.2	0.3	0.2	0.3
50%	2.9	2.8	2.8	1.8	1.7	2.1	2.1	1.8	1.2	0.2	0.6	0.4	0.2	0.2	0.2	0.3
60%	1.8	1.5	0.5	1.8	0.8	0.8	0.5	0.5	0.0	0.4	0.0	0.5	0.2	0.2	0.2	0.3
75%	1.9	1.3	0.8	1.3	0.9	0.8	2.6	2.6	0.0	0.1	0.2	0.0	0.2	0.2	0.1	0.2
100%	0.9	1.1	0.1	1.0	0.6	0.6	0.8	0.6	0.0	0.5	1.1	0.1	0.1	0.2	0.1	0.2
Tata Swatch, allowing for 3 h of contact time before sampling																
0%	7.4	7.2	7.4	7.2	7.1	7.0	7.1	7.0	1.9	2.0	2.1	3.5	1.4	1.8	1.1	1.4
25%	2.8	0.9	2.2	1.9	5.2	5.2	1.7	5.2	0.4	0.8	0.5	0.3	0.2	0.3	0.2	0.3
50%	2.8	2.8	2.1	1.8	2.8	2.2	1.8	2.2	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.3
60%	2.7	1.5	2.8	1.8	1.1	0.5	0.5	0.5	1.0	0.4	1.5	1.1	0.2	0.3	0.2	0.3
75%	1.9	1.3	0.8	1.5	0.9	2.6	2.6	2.6	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.2
100%	0.1	0.1	0.6	0.8	0.6	0.6	0.6	0.6	0.3	0.0	0.1	0.2	0.2	0.2	0.2	0.2
Kent Gold																
0%	1.4	7.2	2.9	3.3	2.7	2.0	7.1	7.0	2.1	6.8	2.0	6.8	1.6	1.8	1.3	1.4
25%	1.5	3.8	1.5	3.1	0.1	0.0	0.1	0.1	0.9	1.9	0.8	1.8	0.4	0.4	0.5	0.6
50%	1.5	2.9	3.0	2.7	1.7	1.8	1.7	1.7	1.1	1.0	2.1	0.9	0.3	0.4	0.4	0.4
60%	1.1	0.1	0.9	3.0	0.9	1.7	2.1	1.3	0.1	0.6	1.7	0.7	0.3	0.3	0.3	0.3
75%	0.6	0.8	0.9	1.9	0.6	0.6	0.6	0.6	0.0	1.4	0.0	0.0	0.2	0.3	0.2	0.3
100%	0.5	0.7	0.9	1.9	0.6	0.6	0.5	0.4	00	1.3	0.0	0.0	0.1	0.2	0.2	0.3
Aquasure PCTi																
0%	3.5	7.2	7.4	1.5	7.1	7.0	2.5	7.0	6.1	6.8	6.8	4.8	1.6	2.2	0.9	1.3
25%	2.5	3.5	1.2	5.0	1.0	0.8	1.1	0.5	2.0	1.4	0.7	1.1	0.1	0.2	0.2	0.2
50%	3.0	2.2	1.8	2.6	1.5	0.8	1.6	1.8	1.3	0.7	1.6	1.3	0.6	0.4	0.6	0.2
60%	0.8	2.7	1.3	2.5	1.5	0.8	1.5	0.7	0.8	0.1	1.8	2.1	0.7	0.5	0.6	0.3
75%	2.6	3.3	1.7	3.7	1.5	2.1	1.8	1.9	2.3	2.0	1.2	0.8	0.3	0.3	0.6	0.3
100%	2.7	2.9	3.0	0.9	2.2	2.0	1.3	1.3	1.6	1.6	1.9	1.6	0.2	0.3	0.4	0.4

of *E. coli* ($p = 0.033$), *B. subtilis* spores ($p = 0.0011$), and microspheres ($p = 0.010$) were significantly greater in the Aquasure PCTi device, and increased against MS2 although not meeting the significance criterion ($p = 0.081$).

Mean reductions did not vary significantly by challenge water for *E. coli* ($p = 0.26$), MS2 ($p = 0.84$), *B. subtilis* spores ($p = 0.96$), or microspheres ($p = 0.19$). Also, we did not observe any differences in mean $\log_{10}$ reductions by ambient temperature ($p = 0.98$, 0.89, 0.70, 0.93, respectively). For each analyte, reductions did decrease significantly over the testing period ($p < 0.001$), suggesting greater performance initially followed by sharp declines (Table 3; Figure 1).

Chemical conditions in challenge waters were maintained and analysed at sampling points. We did not assess turbidity reduction, since pre- and post-treatment turbidity was low (<1 NTU). We noted that the Tata Swatch leached a mean 0.042 mg/l Ag into product water over the course of testing (range: <0.01–0.05 mg/l). Aluminium leaching

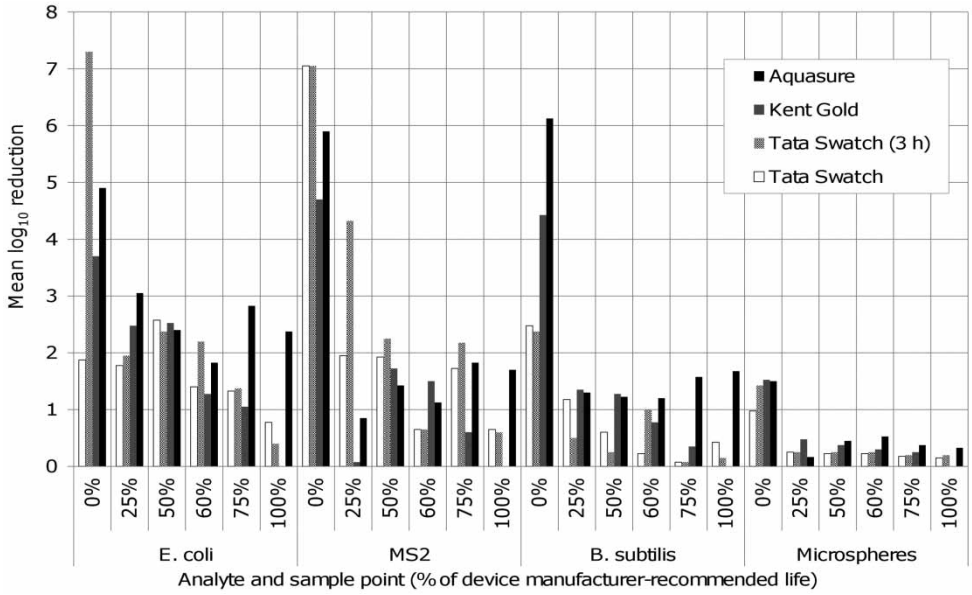

Figure 1 | Summary of mean $\log_{10}$ reduction of *E. coli*, MS2, *B. subtilis* spores, and microspheres by device and lifespan testing point. Each bar represents the mean value of the four conditions (two temperatures and two challenge waters).

from devices was below detectable limits (<0.01 mg/l). All units exhibited clogging and markedly reduced flow rates after 75% of life span was achieved, particularly with the higher turbidity challenge water 2.

DISCUSSION

All devices tested provided measurably improved water over the course of testing, although reductions of microbes and microspheres declined over the course of testing ($p < 0.001$; Table 3; Figure 1). Results therefore suggest that the useful life of all devices has been overestimated by manufacturers, as effectiveness claims are only likely to be met early in testing if at all. Based on mean performance only, technologies would fail to meet WHO minimum recommended performance for microbiological water purifiers at the 'protective' level, which specifies a minimum of 2 $\log_{10}$ (99%) reduction of bacteria and protozoa, and a 3 $\log_{10}$ (99.9%) reduction in viruses. 'Interim' status is based on meeting two of these three conditions and providing evidence of the impact on health. The Aquasure PCTi device would meet this interim target if supported by health impact data, as mean performance exceeded 2 $\log_{10}$ for *E. coli* and *B. subtilis* spores. No such evidence has been reported in the peer-reviewed literature, however. None of the devices tested would have met more stringent applicable international standards such as those published by NSF-International (NSF 2003) or the US Environmental Protection Agency (USEPA 1987). The NSF and EPA standards recommend a 6 $\log_{10}$ reduction of bacteria, 4 $\log_{10}$ reductions of viruses, and a 3 $\log_{10}$ reduction of protozoa. These results may be contrasted with similar testing of other common, commercially available devices for treating household drinking water, including technologies from East Asia (Brown *et al.* 2012) and India (Clasen*et al.* 2006).

We examined the results in light of the claims made by manufacturers. The Tata device performed well under the claim of 99.99% reduction of bacteria and viruses, even allowing for increased contact time with media. The Kent device did produce water that could be claimed as 'healthier', although minimum WHO-recommended performance levels were not met (WHO 2011b). Aquasure's claim that 'all' microbes are eliminated is not tenable given these results, although its performance exceeded that of the other devices tested.

No significant Ag or Al leaching was observed from these devices over a range of use conditions. The measured mean Ag leaching from the Tata device was well under the WHO-recommended limit of 0.1 mg/l (WHO 2011a).

CONCLUSIONS

The microbiological performance data that we have produced is a necessary first step in assessing the potential current and future roles these devices may play in providing safer drinking water in India. Although devices did measurably improve water quality, especially early in testing, reductions in key microbes and microspheres did not indicate that technologies could meet international minimum standards for drinking water treatment. We recommend improvements in treatment technology and limiting unsubstantiated claims about microbiological effectiveness that accompany these products. Given the widespread and growing need for potable drinking water in India (Mudur 2003; Neeri 2004) and the serious risk of sickness and death associated with consuming unsafe water, consumers should not be misled by dubious claims of effectiveness. The importance of truth in advertising for water treatment technologies is of great importance because, in most cases, users cannot verify that devices do what manufacturers claim.

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