Household Water Filter Evaluation

Suitability Report — Lab Research at Consumer Reports

Fall 2015

Massachusetts Institute of Technology
Comprehensive Initiative on Technology Evaluation

Acknowledgments

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List of Acronyms

ATCC	American Type Culture Collection
BoP	Bottom of the Pyramid
CR	Consumer Reports
CU	Consumer Union
GDWQ	Guidelines for Drinking Water Quality
GNE	Gravity Non-Electric
HWF	Household Water Filters
HWTS	Household Water Treatment and Safe Storage
L	Liter
LRV	Log Removal Value
MCC	Maximum Contamination Concentration
MCL	Maximum Contamination Level
MPN	Most Probable Number
µm	Microns (a micron equals 1 millionth of a meter, or 1 thousandth of a millimeter)
NGO	Non-Governmental Organization
NSF	National Sanitation Foundation
NTU	Nephelometric Turbidity Unit
OEM	Original Equipment Manufacturer
PBS	Phosphate-Buffered Saline Solution
QMRA	Quantitative Microbial Risk Assessment
RO	Reverse Osmosis
S1	Suitability
S2	Scalability
S3	Sustainability
TDS	Total Dissolved Solids
USAID	US Agency for International Development
USEPA	US Environmental Protection Agency
WHO	World Health Organization

Introduction

In summer 2014, a research team from the Comprehensive Initiative on Technology Evaluation (CITE) at MIT evaluated household water filters available on the market in Ahmedabad, India. The team worked closely with students and faculty at local universities to assess the suitability, scalability, and sustainability of water filter products by addressing three key questions: Do filters perform their intended purpose? Does the filter supply chain effectively reach consumers? Are filters used correctly, consistently, and continuously over time? The CITE team's lab research findings are presented here.

Suitability in the Lab

CITE defines "suitability" as the technical performance of a product. For CITE's water filter evaluation, suitability was assessed in two ways: by a team of researchers working in a lab setting at the Consumer Reports lab in New York and by a field team working in Ahmedabad, India. This report focuses exclusively on the lab portion of the suitability evaluation. Throughout this report, CITE's suitability work conducted in the lab is referred to as "S1-Consumer Reports." The overall goal of CITE's S1-Consumer Reports work has been to investigate the performance and use of different Indian water filter models so that donors, international agencies, and consumers can make more informed household water filter purchase and use decisions. The result of CITE's effort is a Consumer Reports-style comparative ratings chart, which differentiates between various filter models found in the marketplace in Ahmedabad, based on their key attributes and features.

Suitability Objectives

CITE's lab-based suitability research had four objectives:

<u>Development of the Test Methods</u>: CITE needed to adjust test methods to meet an emerging market context. Performance attributes that are relevant to a water filter evaluation in a water-poor situation, such as *E. coli* removal and turbidity removal, are not part of the Consumer Reports standard protocol for evaluating filters in the US market.

<u>Development of the Test Rig</u>: The Consumer Reports test rig required major modifications to make it appropriate for CITE's water filter evaluation.

<u>Development of the Challenge Water</u>: Protocols were developed for consistently creating high levels of *E. coli*, turbidity, and total dissolved solids (TDS) in the challenge water and a benign (no chlorine) base "carrier" water for these contaminants.

<u>Testing of Water Filter Performance</u>: CITE scored and rated filters based on the results of the performance testing to produce a Consumer Reports-style comparative ratings chart.

Water Filter Categories and Models

Fifteen models of water filters, within three water filter categories, were tested at the Consumer Reports lab as part of the CITE water filter evaluation. This includes: four conventional particle removal filters, nine gravity non-electric (GNE) filters, and two reverse osmosis (RO) filters chosen to be representative of the water filters commonly available in the market in Ahmedabad. These 15 models were purchased in Ahmedabad, India, and shipped to the Consumer Reports lab in New York. This section details the filtration process, the three water filter categories investigated, and the 15 models tested in the Consumer Reports lab.

Filtration Processes and Categories

<u>Conventional particle removal filtration</u> is a water treatment process widely applied in most water treatment facilities, from large-scale urban systems to household-scale water filters. A conventional particle filter can consist of cloth, mesh, sand, gravel, ceramic, or plastic materials; it potentially removes bacteria, protozoa, and particles, as well as sand, clay, and dirt particles that range in size from 1 to 1000 microns (µm). A grain of beach sand ranges from about 100 to 2000 µm. Particles larger than 50 µm are visible to the naked eye; particles smaller than 50 µm, including microbes, are detectable only under a microscope.

<u>Microfiltration</u> separates solids from water via the mechanisms of size exclusion and/or particle capture. Suspended particles and microbes are captured on the surface or inside a micro filter, with dissolved substances and water passing through the filter. Microfiltration is capable of removing particles in the size range of 0.1 to 1 μm. This size filter may be used to remove bacteria and large pathogens, such as Giardia and cryptosporidium. However, additional chemical disinfection is required to remove viruses. Ceramic candle filters and ceramic pot filters are examples of this category of filters, which rely on small pores of ceramic materials to remove dirt, bacteria, and protozoa.

Ultrafiltration is a pressure-driven filtration process for fractionating and concentrating solutions containing suspended colloids and solutes of high molecular weight. The mechanism of ultrafiltration is size exclusion or particle capture. Ultrafiltration takes out particles in the size range of 0.01 to 0.1 μm, and is mostly applied in industry for purifying and concentrating macromolecular (10^3 to 10^6 Daltons (Da[1]) solutions, especially protein solutions.

Nanofiltration is a membrane process that uses cylindrical tubes with water passing through the pores of the membrane at a 90° angle. This category is smaller than microfiltration and ultrafiltration, but larger than reverse osmosis membrane filtration. Nanofiltration membrane pore sizes range from about 1 to 10 nanometers (nm), and the filtration level takes out particles that are 1 nm in size. Nanofiltration is mostly used with water containing low total dissolved solids, such as surface water, as well as to remove disinfection by-product precursors, such as natural or synthetic organic matter.

Reverse osmosis filtration is a process that uses high pressure to push the water through the RO membrane. It results in the solute (contaminants) retained on the pressurized side of the RO membrane as brine (or wastewater) and the pure solvent (clean water) is allowed to pass to the other side of the membrane.

RO is easily understood by contrasting it with micro, ultra and nanofiltration. The predominant removal mechanism in micro/ultra/nano filtration is mechanical straining, or size exclusion, so the process can theoretically achieve perfect exclusion of particles regardless of operational parameters such as influent pressure and concentration. In contrast, reverse osmosis involves a diffusive mechanism, so that separation efficiency is dependent on solute concentration, pressure, and water flux rate.

Reverse osmosis can remove particles less than 0.1 nm. It is used to remove many types of ions and molecules from solution, and is highly effective in removing organic and inorganic contaminants, bacteria, and viruses.

The pore size, molecular weight cutoff, and particles removed by each filtration process can be seen in Table 1.

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1 Dalton (Da) is the standard mass unit on an atomic or molecular scale. It is defined as one-twelfth of the mass of an unbound neutral atom of carbon-12 in its nuclear and electronic ground state, and has a value of $1.660538921(73) \times 10^{-27}$ kg.

Table 1. Filter Categories, Pore Sizes, Molecular Weight Cutoff, Filtration Pressure, and Particles Removed (Baker, 2012)

Filter Category	Sub-Categories	Pore Size	Molecular Weight Cutoff*	Particles Removed
I. Conventional Particle Filtration		1 to 1000 µm	-	sand, clay, dirt
II. Gravity Non-Electric (GNE)	Microfiltration	0.03 - 10 µm	>100 kDa	sand, clay, silt giardia lamblia, cryptosporidium cysts, algae, some bacterial species
	Ultrafiltration	0.002 – 0.1 µm	10-100 kDa	bacteria, macromolecules, proteins, larger viruses
	Nanofiltration	~1 nm	1-10 kDa	all cysts, bacteria, viruses, humic materials, hardness
III. Reverse Osmosis (RO)		< 0.1 nm	< 100 Da	all inorganic contaminants, small organic molecules

The gravity non-electric (GNE) filter is a special category defined by CITE for the purpose of this study. It spans the range from microfiltration to nanofiltration, and was chosen by the CITE team as a simplification of household filter products found in the Indian marketplace.

Table 2 shows all models tested at Consumer Reports.

Table 2. Water Filter Models Tested at Consumer Reports Lab in N.Y.

Filter Category	Model	Technology Type	Manufacturer	Price (Rs)	Price (USD)	Parts (USD)
Particle Removal Filters	Cloth #1	Particle Filter		60	$1.0	
	Cloth #2	Particle Filter		60	$1.0	
	Cloth #3	Particle Filter		60	$1.0	
	Jali Mesh	Particle Filter	Robin	30	$0.5	
GNE Filters	Stainless Steel Water Container	Ceramic Candle Filter	Expresso			
	Swach Christella Plus	Nano Filtration, Silver	Tata	1000	$17	$25
	PureIt Compact - 14L	Micro Filtration, Activated Carbon, Chlorine	Hindustan Unilever	1525	$25	$25
	LifeStraw	Ultra Filtration	Prestige	3495	$58	
	Aquasure Kitanu Magnet	Nano Filtration	Eureka Forbes	2400	$40	$25
	Gold Plus - 20L	Ultra Filtration	Kent	2600	$43	$25
	Swach Smart 1500liters	Nano Filtration, Silver	Tata	1199	$20	$5.8
	Swach Smart	Aquasure Kitanu Magnet	Tata	999	$16	
Reverse Osmosis Filters	Dolphin	Reverse Osmosis	Clean Water	6500	$108	$100
	Dolphin	Reverse Osmosis	Blue Diamond	6500	$108	$100
	Dolphin	Reverse Osmosis	Dolphin Gold	6500	$108	$100
	Swach Platina Silver	Reverse Osmosis	Tata	14000	$233	$150

Conventional Particle Removal Filters in Ahmedabad

The conventional particle filters found in the Indian marketplace in the city of Ahmedabad included cloth and *Jali* mesh filters, as seen in Figure 1. These common kitchen items are widely used in Ahmedabad households, especially in low-income families, to improve drinking water quality.

Figure 1. *Jali* Mesh (left) and Cloth (right) Filters

Cloth Filter

The S1-Consumer Reports research team chose three kinds of cloth to represent the “best,” “medium,” and “lowest” quality in the Ahmedabad marketplace based on the tightness of the weave. They are respectively labeled as Cloth #1, #2, and #3. A square meter of a cloth filter costs only about one US dollar.

According to the CITE field team, with whom lab team worked closely, most people in Ahmedabad use the cloth in one or two layers rather than four. Figure 2 shows examples of the cloth filters that the CITE field team found in Ahmedabad households. Normally, the cloth is tied around a faucet or put over a storage tank to filter water. It is washed or changed once the user believes it to be dirty.

Figure 2. Cloth Filters Found in Ahmedabad Households

The pore sizes of one layer of Cloths #1, #2, and #3 were measured using an Olympus FH Microscope (220959) with the highest magnification of 4000x (Figure 3a) and the FEI/Philips XL30 FEG ESEM microscope (Figure 3b). The pore size of Cloth #1 is less than 30 µm; Cloth #2, about 100 µm; and Cloth #3, about 200 to 300 µm. Generally, cloth filters in Ahmedabad can only remove large particles such as sand.

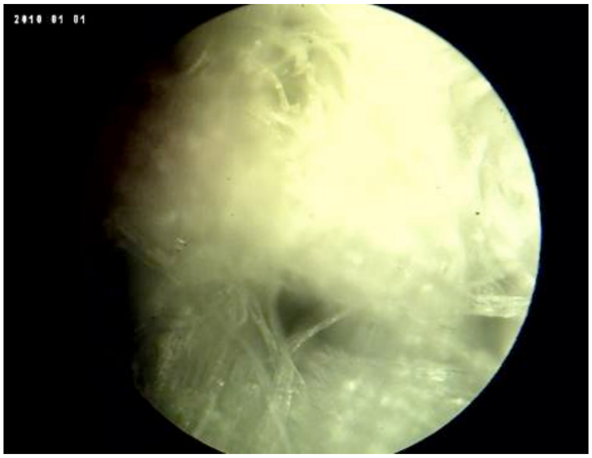

Figure 3a. Micrograph of Cloth #1

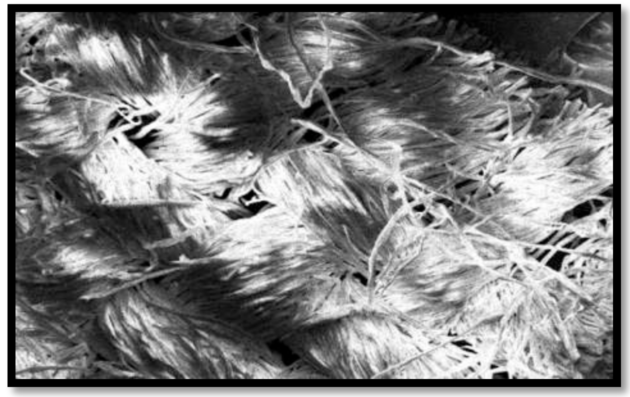

Figure 3b. Higher Magnification of Cloth #1 Using an FEI/Philips XL30 FEG ESEM Microscope

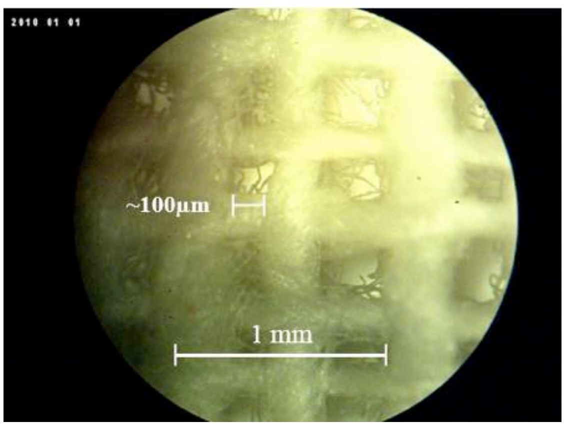

Figure 3c. Micrograph of Cloth #2

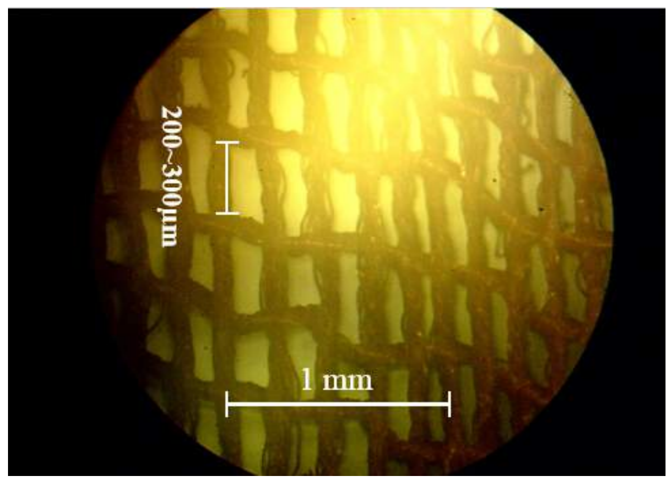

Figure 3d. Micrograph of Cloth #3

Cloth filters are inexpensive and easy to use, but are not effective at removing contaminants of concern such as *E.coli* or total dissolved solids. Drinking water can become contaminated if the cloth is not kept clean.

Mesh Filter

Five different models of *Jali* mesh filters were purchased in Ahmedabad and shipped to the Consumer Reports lab for testing:

- Robin Brand Mesh

- Robin Rimpi-99 Mesh
- Robin Big Boss Mesh
- Akash Jaldhara Mesh
- Marshal Zeba Mesh

All of the models were two-layer mesh filters with the same tightness and weave.

Jali mesh filters are placed over a container that stores the filtered clean water for daily use. Figure 4 shows how an Indian woman uses a *Jali* mesh filter in her kitchen. Each mesh filter costs about US $0.50.

Figure 4. Mesh Filter Used in an Indian Household

The weave of the *Jali* mesh filters was also measured using a microscope (Olympus FH Microscope (220959) with the highest magnification of 4000x. Figure 5 shows the pore sizes of one- and two-layer mesh filters. The one-layer mesh filter has a pore size of 300µm, which is similar to Cloth #3.

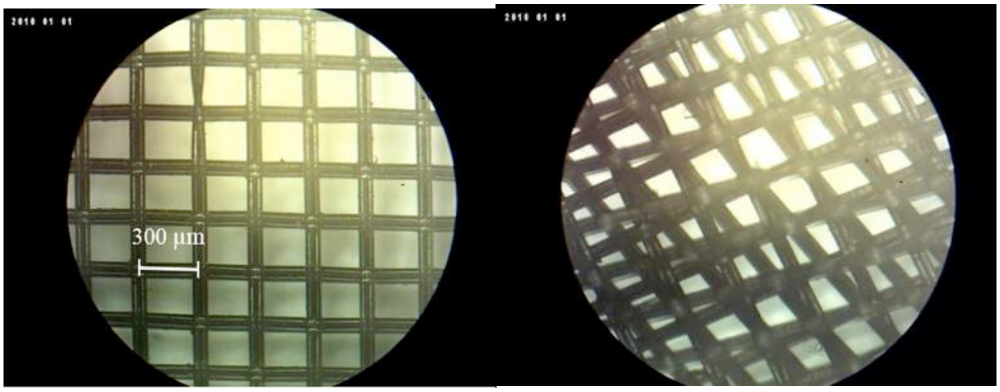

Figure 5. Micrograph of Mesh Filters (left: one layer; right: two layers)

Gravity Non-Electric (GNE) Filters in Ahmedabad

GNE filters are gravity-driven, manual-fill filters that do not need electricity. They are easy to use and maintain, and are often put on a kitchen countertop. Most GNE filters operate in the microfiltration or ultrafiltration range, with a few in the nanofiltration range. They cost much more than the cloth or mesh, but much less than the RO filter systems. Table 3 lists the manufacturers and prices of the GNE filter models tested at the Consumer Reports laboratory.

Table 3. GNE Filter Models Tested

Category	Model	Technology	Manufacturer	Price (USD)
GNE	Stainless Steel Water Container	Ceramic Candle Filter	Expresso	N/A
	Swach Cristella Plus	Nano Filtration, Silver	Tata	$17
	Pureit Classic 14L	Micro Filtration, Activated Carbon, Chlorine	Hindustan Unilever	$17
	LifeStraw	Ultra Filtration	Prestige/Vestiguard	$50
	Aquasure Kitanu Magnet	Nano Filtration	Eureka Forbes	$42
	Gold Plus – 20 L	Ultra Filtration	Kent	$43
	Swach Smart 1500 liters	Nano Filtration, Silver	Tata	$20
	Swach Smart 3000 liters	AquaSure Kitanu Magnet	Tata	$17
	Everpure Unbreakable	Activated Carbon	N/A	$23

Expresso Stainless Steel Water Container

The Expresso stainless steel water container is a micro-filter (see Figures 6 and 7) that uses two ceramic candle elements. The filter consists of two stainless steel containers, and the white clay candle elements are screwed into the base of the upper container. The very fine pore sizes differ and can be as small as 1 µm (Sagara, J., 2000). Candle elements have very slow flow rates. To increase the clean water flow rate, a water filter of this type usually contains two to three candle elements. Dies' research shows that five candle elements of different compositions resulted in flow rates ranging from 300 ~ 840 mL/hr./candle (Dies, 2003).

Figure 6. Expresso Stainless Steel Water Container

Figure 7. Ceramic Candle Element

According to the instructions for this Expresso stainless steel model, the ceramic elements must be soaked in clean water for two days before using the filter. The first-use filtered water should not be used as drinking water. The flow rate is very slow in the beginning, but will increase after 14 days' of use when all the pores fully open. For maintenance, the user must keep the ceramic filter candles clean by regularly brushing the surface gently under clean flowing water. The price of this Expresso model is $15.

Tata Swach Cristella Plus

The Tata Swach Cristella Plus model is manufactured in India (see Figure 8), and is composed of three parts. The upper part contains: (1) a pre-filter made from fabric that removes big particles;

(2) a reservoir for the untreated water; and (3) a portion where the Tata Swach bulb can be attached (see Figure 8). The lower chamber is a safe storage container, which collects clean water that is accessible to the user via a water tap placed at the bottom of the container. The storage capacity is 9 L, and the Swach bulb has a purification capacity of 3000 L. The flow rate of the filter is claimed to be 3–4 L/hr. According to the manufacturer’s instructions, a device in the bulb can stop the flow of water once the purifying power of the bulb is exhausted. A fuse in the bulb indicates when the bulb should be replaced.

Figure 8. Tata Swach Cristella Plus (left) and Swach Bulb[2] (right)

The core filtration part of this model is the Tata Swach bulb, which uses silver nanotechnology as its means of water purification. According to the manufacturer, this Swach bulb technology uses rice husk ash impregnated with nano (1×10^{-9}) silver particles and contains activated silicon and carbon. The filtration bulb can remove turbidity, and the silver particles can inhibit bacteria multiplication. The nano-sized particles increase the filter surface area so that the bacteria have enough reaction time (India Center for Science and Environment, 2010). This filter can remove 10^9 bacteria and 10^7 viruses without the harmful chemicals used for purification.

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[2] http://www.snapdeal.com/product/tata-swach-filter-candle-bulb/

Tata recommends that the pre-filter be washed at least once a week and that the mesh at the bottom of the bulb be cleaned at least once a month. Before the first use, fill the upper container with water, wait until it all goes into the bottom safe storage container, and then empty the bottom container. After this process, the filter can be used to provide clean water. The price of the Tata Swach Cristella Plus is $17.

Tata Swach Smart

The Tata Swach Smart (see Figure 9) has a storage capacity of 7.5 L, uses silver nanotechnology in its bulb, and has two containers. The upper container has a microfiber, pre-filter on the top and a Swach bulb attached at the bottom; the clean water is stored in the bottom container after filtration. The bulb also has a device that indicates when it should be replaced. According to the instructions, the pre-filter should be washed at least once a week, and the mesh at the bottom of the bulb should be washed at least once a month.

Before the first use, fill the upper container with water, wait until it all goes into the bottom container, and then empty the bottom container. After this process, the filter can be used to provide clean water. The price of the Tata Swach Smart is $20.

Figure 9. Tata Swach Smart[3] (left) and Swach Bulb[4] (right)

[3] http://www.tataswach.com/know_tata_swach/tata_swach_smart.html

[4] http://www.cromaretail.com/Tata-Swach-Bulb-(Yellow)-pc-21718-462.aspx

Hindustan Unilever PureIt Classic 14L

The Hindustan Unilever PureIt Classic 14L (see Figure 10) is a multistage water filter. The water first goes into a microfiltration pre-filter and then passes through an activated carbon filter. Activated carbon is a special form of carbon with small pores that increase the surface area available for adsorption or chemical reactions (Mattson, J. S., 1971). According to the manufacturer, this activated carbon filter removes dirt, parasites, and pesticide residuals. Next, the water goes to a “Germkill Processor” using “programmed chlorine release technology” to kill harmful viruses and bacteria. Finally, the water passes through a component called the “Polisher,” which removes residual chlorine and gives the clear water a good taste. Unilever claims that this model can remove 10^7 viruses in 1 L of water.

The top chamber has a capacity of 5 L, and the transparent safe storage chamber has a capacity of 5 L. The Germkill Kit™—including the activated carbon filter, the Germkill processor, and the polisher—has a claimed purification capacity of 1000 L, which, for a family of five, translates to a 50-day lifetime, assuming 4 L per person per day. It also has a Germkill Life Indicator that gives advance warning before the Germkill Kit™ needs to be changed. The price of the Hindustan Lever PureIt Classic (14 liters) is $17.

Figure 10. Hindustan Unilever PureIt Classic 14L[5]

[5] http://www.pureitwater.com/IN/products%E2%80%8E/pureit-classic-14l

Prestige LifeStraw

The water filtration process for the Prestige LifeStraw (see Figure 11) has three stages: a microfiltration pre-filter that removes relatively big particles; a carbon block that removes chlorine, sediment, volatile organic compounds, taste, and odor; and an ultrafiltration membrane, which is the core technology. The ultrafiltration membrane can remove 99.9999% bacteria, 99.99% viruses, 99.99% protozoan parasites, and particles larger than 0.02 μm while using no chemical for filtration.

Prestige LifeStraw has a total capacity of 18 L, whereas the clean water storage tank is half that size (9 L). It has a purification capacity of 4500 L of water before the ultrafiltration membrane needs to be replaced. The price of the Prestige LifeStraw is $50.

Figure 11. Prestige LifeStraw

Eureka Forbes AquaSure Kitanu Magnet

The Eureka Forbes AquaSure Kitanu Magnet (see Figure 12, left) has three water filtration stages: a microfiltration pre-filter that removes particulates; a sediment filter consisting of a microfiber mesh with high surface area that removes impurities not visible to the eye; and the core Kitanu Magnet with "Positive Charge Technology" ™ (PCT) cartridge. According to the manufacturer, its nanofibers "attract and pull out bacteria and viruses," and the cartridge does not require chemicals to purify water.

The top and bottom containers have a storage capacity of 9 L and 11 L, respectively. A specially designed float at the bottom of the top container can regulate the flow so that both containers can store water. The Kitanu Magnet cartridge (see Figure 12, right) has a natural shut-off function that closes gradually when the cartridge approaches its end-of-life. The cartridge should be replaced after every 750 L of water, the microfiltration pre-filter should be washed every 15 days, and the initial run of filtered water through the cartridge should be discarded. The price of the Eureka Forbes AquaSure Kitanu Magnet is $42.

Figure 12. AquaSure Kitanu Magnet (left) and Kitanu Magnet “Positive Charge Technology” Cartridge[6] (right)

KENT Gold Plus 20L

The water filtration process for the KENT Gold Plus 20L model (see Figure 13) has three stages. The untreated water is filled into the top tank and then passes through the sediment filter, a conventional particle filter, which removes suspended impurities; the silver impregnated carbon granules remove chlorine and odor; and then the water flows through the core ultrafiltration membrane, which removes bacteria and can achieve a 99.6% reduction of cysts.

The top tank has a capacity of 7 L, and the bottom tank can hold 13 L. According to the user manual, the purification capacity for the ultrafiltration membrane is 4000 L, and for the carbon filter it is 900 L. The flow rate is 18 L/hr.

The safe storage tank should be washed with clean water once every seven days; the sediment

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[6] http://www.shoppingstore.in/index.php?route=product/product&product_id=132

and carbon filters should be cleaned at least once in 30 days; and the ultrafiltration membrane should be backwashed at least once in 30 days. The sediment filter must be changed after three months; the carbon filter should be changed after six months; and the ultrafiltration membrane should be changed every 12 months. The price of the KENT Gold Plus (20 liters) is $43.

Figure 13. KENT Gold Plus 20L[7] (left) and Ultrafiltration Membrane[8] (right)

Everpure Unbreakable

The Everpure Unbreakable model has two filters (see Figure 14). A microfiltration ceramic filter is located in the upper container, and a sediment filter—which is filled with granular activated carbon, silica stand, zeolite, and mineral stones and mineral sand—is attached to the bottom of the upper container. It has a storage capacity of 15 L and can provide 35 to 65 L of clean water every day at a flow rate of 2.5 L/hr. to 5L/hr.

Since there is no seal ring between the upper and bottom containers, multiple test samples of this model were found to leak severely. As a result, the Everpure Unbreakable model was not tested for its performance in the laboratory. The price of the Everpure Unbreakable was $43.

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[7] http://www.latestviews.com/home-appliances/water-purifiers/kent-gold-plus-water-purifier/product-gallery/

[8] http://www.ebay.in/itm/Kent-Gold-Gold-Optima-Star-Spare-Part-1-UF-Membrane-/181584229338

 

Figure 14. Everpure Unbreakable (left) and Mineral Filter[9] (right)

REVERSE OSMOSIS FILTERS IN AHMEDABAD

The reverse osmosis (RO) water filter has an important advantage over the particle removal and GNE filters: it can remove total dissolved solids and hardness.

The key component of an RO water filter is its RO membrane. Figure 15 below shows how the RO membrane operates.

[9] http://www.naaptol.com/water-filters-and-purifiers/everpure-7-step-mineral-water-purifier/p/12442950.html

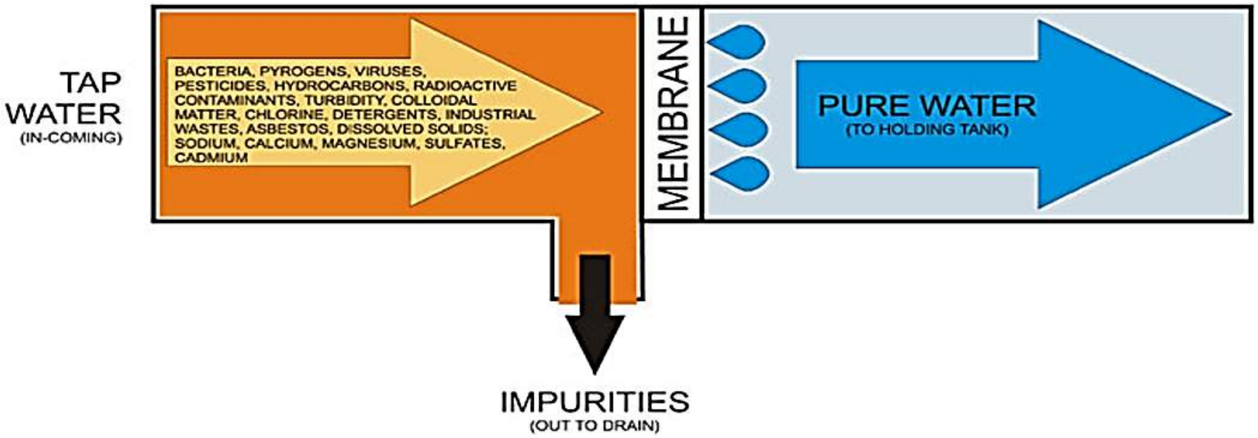

Figure 15. Reverse Osmosis System Schematic[10]

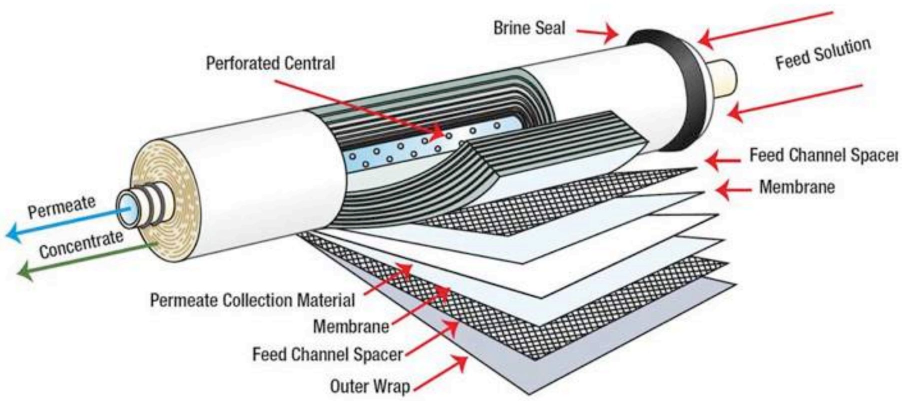

Figure 16. Diagram of a Reverse Osmosis Membrane[11]

Normally, at least one pre-filter and one post-filter are located before and after the RO membrane. The pre-filters remove larger particles in order to extend the life of the membrane; the post-filters are usually filled with activated carbon to give the clean water a better taste.

The Indian RO marketplace is focused on the middle- to high-income groups due to the high purchase price (US $98 to $300) and operating costs of RO filters. Known for producing a large

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[10] http://espwaterproducts.com/about-reverse-osmosis.htm

[11] http://erkinchik.wordpress.com/ro-membrane-housing-hook-up/

amount of wastewater (i.e., brine or concentrate), the RO filter produces three times as much wastewater as much as clean water. For municipalities where water is scare and/or expensive to buy, wastewater generation is both an environmental sustainability and cost concern.

There are two types of RO filters in the Indian marketplace: locally assembled “Dolphin” ROs and branded ROs. CITE’s fieldwork determined that the RO market in India has been growing significantly with the introduction of Dolphin due to its much lower price. Table 4 below compares the performance of the Dolphin ROs to established RO brands such as the Tata Swach Platina Silver.

The following RO filters were purchased in India and tested at the Consumer Reports lab in New York.

Table 4. RO Filter Models Tested at the Consumer Reports Lab in N.Y.

Category	Model	Model Type	Price (USD)
RO	Blue Diamond	Non-branded, Dolphin model	$98
	Clean Water	Non-branded, Dolphin model	$98
	Dolphin Gold	Non-branded, Dolphin model	$98
	Tata Swach Platina Silver	Branded model	$233

Locally Assembled Dolphins

Three Dolphin models were tested at the Consumer Reports lab: Blue Diamond, Clean Water, and Dolphin Gold. The Clean Water model was lifetime testing, but the Blue Diamond and Dolphin Gold models were only tested for a short period due to time constraints.

All of the Dolphin filters have the same basic design and five stages (see Figure 17):

Stage 1: A 5 μm PP (pleated polypropylene) sediment filter outside of the filter that removes suspended impurities such as sand, dust, and dirt.

Stage 2: An inline sediment cartridge that eliminates other particles such as bacteria, viruses, colloids.

Stage 3: A pre-carbon filter that removes color, odor, chlorine, and pesticides.

Stage 4: An RO membrane that eliminates toxins, chemicals, total dissolved solids, viruses, and bacteria.

Stage 5: A post-carbon filter that imparts a natural taste to water.

The clean water exiting these cartridges is stored in a 9 L tank. When the tank is full, a float stops the RO from operating. Inside each Dolphin filter, there is a pressure pump and an AC-DC voltage transducer. Figure 18 shows the front and inside views of a Dolphin filter.

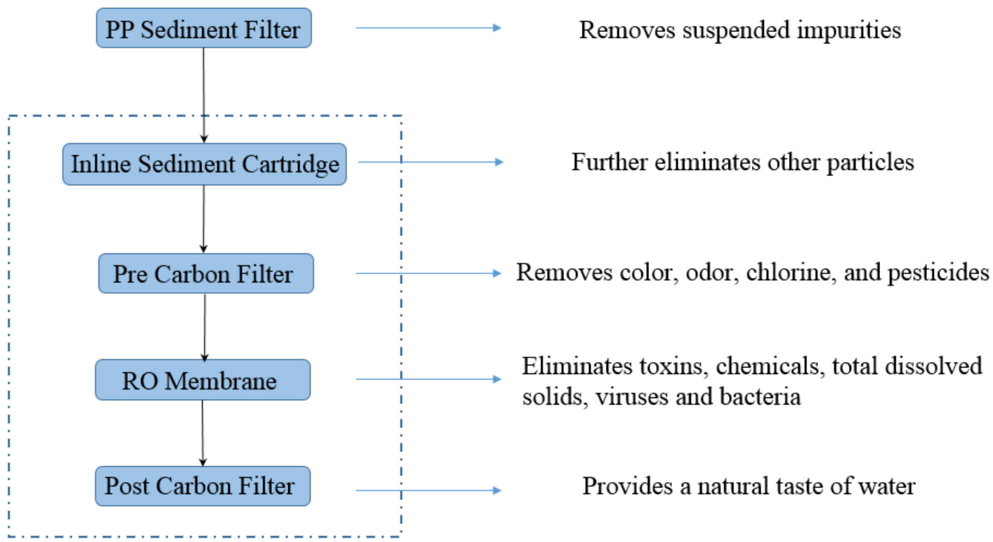

Figure 17. Dolphin Design Stages and Their Functions

Figure 18. Front and Inside Views of a Dolphin

When customers buy a Dolphin, a technician will help them to assemble the product in their homes. The instructions on the package box claim that a Dolphin has a filter capacity of 90 L/day at 25°C.

Tata Swach Platina Silver

Tata Swach Platina Silver is a branded RO filter (see Figure 19) that also has five stages:

Stage 1: A 10 µm sediment filtration cartridge that reduces coarse impurities, such as dust and sediments, which are greater than 10 µm.

Stage 2: Bacteriostatic granular activated carbon (GAC) with nano-silver impregnation technology that reduces chlorine, odors, volatile organic compounds, and pesticides. The nano-silver impregnation technology used in this cartridge reduces the chance of biofouling and hence increases the life of the carbon cartridge.

Stage 3: A 5 µm sediment filtration cartridge removes finer impurities, such as dust and sediments, which are greater than 5 µm.

Stage 4: A National Science Foundation-certified RO membrane that has fine pores as low as 0.0001 µm. It reduces water contaminants such as dissolved salts, pesticides, and heavy metals, as well as waterborne micro-organisms such as viruses and bacteria.

Stage 5: Post-bacteriostatic granular activated carbon (GAC) with nano-silver impregnation technology that imparts bacteriostatic properties to the purified water and enhances the taste of water.

Figure 19. Tata Swach Platina Silver[12]

Figure 20. Tata Swach Platina Silver under Testing

Tata Swach Platina Silver has a 7-liter “zero contamination” storage tank to store clean water. Inside the filter are a pressure pump and a voltage transducer. This model has an auto-flushing system to clean the membrane and a Double-i-Care™ indicator. If the first sediment filtration cartridge clogs, the low-pressure switch will be activated and the Double-i-Care indicator will show a fault indication.

The inlet water pressure needs to be within the range of 5 psi to 35 psi, and the temperature should be between 2℃ and 49℃. It has a purification capacity of up to 12 L/hr. under the conditions of 10 psi input pressure and 750 ppm TDS at 25℃.

Methodology

Product Attributes

After referring to the World Health Organization (WHO) and other literature reviewed in Liu (2015), CITE determined an evaluation sub-set of six water filter performance attributes based on water quality as observed by the field team in Ahmedabad. These attributes were: *E. coli* removal, turbidity removal, total dissolved solids (TDS) removal, RO clean water flow rate, RO % recovery (of clean water), and filter end-of-life (i.e., “lifetime” or “clogging”). Below is a description of each attribute. Each filter model was tested with multiple samples for each of the attributes except for the filter end-of-life when a single sample was taken due to the length of the procedure required.

CITE did not evaluate filters for chemical contaminants such as arsenic or fluoride for two reasons. First, arsenic and fluoride are not common in the Ahmedabad water supply, so would not be relevant to this study. Second, the WHO deems infectious diseases caused by microbial contaminants to be the “most common and widespread health risk associated with drinking water.”

[12] http://www.tataswach.com/know_tata_swach/tata_swach_silver_platina_ro.html

***E. coli* Removal**

E. coli, of the genus *Escherichia*, is an anaerobic, rod-shaped bacterium about 2.0 µm in length and 0.25-1.0 µm in diameter (Kubitschek, H.E., 1990). It is commonly found in the intestine of warm-blooded organisms (Singleton P., 1999). *E.coli* removal was chosen to represent a filter's ability to remove bacteria as this is the most widely used indicator of fecal contamination of drinking water. Percentage removal and log removal value (LRV) both indicate this attribute. LRV can be calculated as:

$$LRV = -log\ (\frac{MPN\ in\ influent}{MPN\ in\ effluent})$$

Equation 1

Most probable number (MPN) of bacteria is a method for estimating the density of bacteria or other organisms in a liquid, such as water or food, without doing a direct count of bacterial colonies cultured on a Petri dish, and using probability to determine a quantitative result. The MPN method was used with an IDEXX Quanti-Tray to test for, and estimate, the quantitative results.

The WHO "International Scheme to Evaluate Household Water Treatment Technologies," used an input *E. coli* concentration of around 10^5 colonies per milliliter in their study of household water treatment technologies (WHO, 2014a). As per the WHO microbiological organisms and reduction requirements (Table 5), when the *E.coli* LRV is higher than 4, the filter is rated as "highly protective"; when the percentage removal is between 99% and 99.99%, the filter is defined as "protective or limited protective."

Table 5. Microbiological Organisms and Reduction Requirements (WHO, 2014a)

Organism	Pretreatment Challenge[1]	Minimum Required Reduction[2] (log and %)			
		Highly Protective		*Protective or Limited Protection*	
Bacteria: *E. coli* (ATCC 11229)	$\geq 10^5$/100 mL	≥ 4	≥ 99.99	≥ 2	≥99
Virus[3]: MS-2 coliphage (ATCC 15597-B1, *E. coli* host ATCC 15597 and phiX-174 ATCC 13706-B1; *E. coli* ATCC 13706 (host)	$\geq 10^8$/L	≥ 5	≥ 99.999	≥ 3	≥99.9
Cyst[4]: *Cryptosporidium parvum* infectious oocysts	$\geq 5x10^5$/L	≥ 4	≥ 99.99	≥ 2	≥99

In the second edition of *WHO Guidelines for Drinking Water Quality* (WHO, 1997), five risk levels were defined according to *E. coli* concentration in the water sample (Table 6).

Table 6. Risk Level from *E. coli* (WHO, 1997)

Risk Level	*E. coli* in sample (coliform forming unit per 100 mL)
Conformity	< 1
Low	1 – 10
Intermediate	10 – 100
High	100 – 1000
Very High	> 1,000

CITE developed the evaluation system shown in Table 7 using Table 6 as a reference.

Table 7. CITE's System for Evaluating *E. coli* Removal Performance of the Filters

Performance	% *E. coli* Removal	LRV
Excellent	> 99.99	> 4
Very Good	99.9~99.99	3~4
Good	99~99.9	2~3
Fair	90~99	1~2
Poor	< 90	< 1

Turbidity Removal

Turbidity in water is caused by suspended particles or colloidal matter that obstructs light transmission through the water. The inlet "challenge" water had a turbidity of 40 NTU (nephelometric turbidity unit) based on the WHO "Protocol" (WHO, 2014b). The effectiveness of turbidity removal was measured as percentage removal. In the municipal water in Ahmedabad, the turbidity typically is quite low ranging from 0.1 to 0.5 NTU, and turbidity of surface waters ranges from 4 to 11 NTU (Devangee, S., 2013). Thus, the turbidity of the Consumer Reports team's challenge water is much higher than that found in Ahmedabad because: (1) it represented the worst-case scenario, and (2) using a fixed concentration guided by WHO makes it easier to compare our findings with the research of household water treatment products worldwide. The WHO Protocol specified the use of a specially processed test dust product, or A2 dust, which can simulate turbidity in water at a lab scale. The A2 test dust has particle sizes ranging from 0.2 to 176 µm. The CITE team defined performance in terms of turbidity removal as shown in Table 8.

Table 8. Scoring of Turbidity Removal of the GNE Filters

Performance	Turbidity Removal (%)
Excellent	80~100
Very Good	60~80
Good	40~60
Fair	20~40
Poor	0~20

Total Dissolved Solids Removal

Total dissolved solids (TDS) removal is a measure of the combined content of all inorganic and organic substances contained in a liquid in molecular, ionized, or micro-granular suspended form. It comprises inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates) and small amounts of organic matter that are dissolved in water. Measurement at the Consumer Reports lab was performed using a TDS conductivity meter[13]. TDS in drinking water originates from natural sources, sewage, urban runoff, and industrial wastewater. The palatability of drinking water has been rated by panels of tasters in relation to its TDS level as shown in Table 9 (WHO, 2006).

Table 9. Palatability of Drinking Water (WHO, 2006)

Description	TDS (mg/L)
Excellent	< 300
Very Good	300 – 600
Good	600 – 900
Fair	900 – 1200

[13] Conductivity refers to the electrical conductivity a solution exhibits. Typically, it is available as KCl and not NaCl. The units are expressed as micro mho/cm or micro Siemens/cm.

Poor	1,200

Figure 21 (Murcott S., 2014) shows the box plot[14] of TDS in Ahmedabad source waters. The green line indicates the Indian Standard Requirement (Acceptable Limit), which the CITE team used as the drinking water quality standard. The red line shows the Indian Standard (Permissible Limit). On average, groundwater in Ahmedabad contains 1,079 mg/L TDS, based on the results from the CITE Suitability India field team (S1-India). TDS for the challenge water was set at 1500 mg/L by the S1-Consumer Reports team, which is the level suggested by the WHO Protocol (WHO, 2014b). This represents the worst-case scenario, and makes it easier to compare our findings with research of household water treatment products around the world. In our protocol, Epsom salts, magnesium sulfate ($MgSO_4$), which contribute 100% to hardness, were used to evaluate TDS concentration and removal.

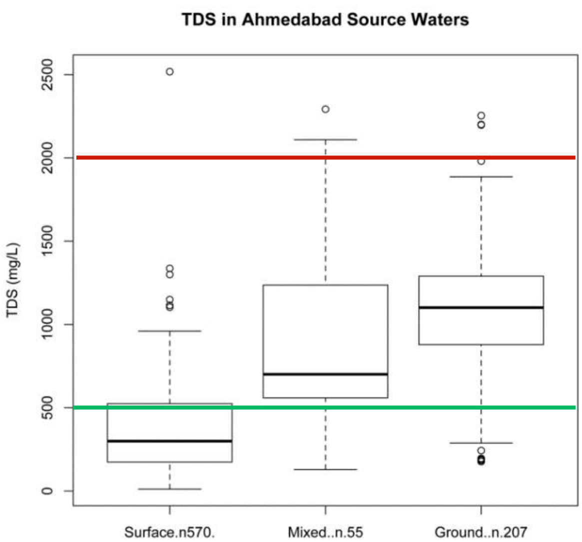

Figure 21. Box Plot of TDS in Ahmedabad Source Waters (Murcott, S., 2014)

The CITE team's scoring of TDS removal of the GNE filters used the same scoring as that used for turbidity removal (compare Table 8 and Table 10)

[14] Box plots display differences between samples without making any assumptions of the underlying statistical distribution: they are non-parametric. It is a convenient way of graphically depicting groups of numerical data through their five-number summaries. They include the smallest observation known as sample minimum, lower quartile (Q1), median (Q2), and upper quartile (Q3), as well as the largest observation also known as sample maximum.

Table 10. Scoring of TDS Removal of the GNE Filters

Performance	TDS Removal (%)
Excellent	80~100
Very Good	60~80
Good	40~60
Fair	20~40
Poor	0~20

Clean Water Flow Rate

Clean water is the product of water filtration, which can then be acceptable as drinking water. In the water industry, treated water is referred to as "product water." The flow rate of clean water through a filter or other treatment system determines whether consumers can get enough water for daily use. As mentioned in the literature review, at a minimum, people need to drink from 1.5 to 2.5 L per person per day to stay healthy (Pimentel, D., 2004); whereas, the WHO (Howard, G., 2003) suggests a minimum of 7.5 L per person per day, based on requirements of a lactating women in a tropical climate, and assuming that 7.5 L includes water for cooking. The S1-Consumer Reports team assumed that 1.6 L per person per day, and 8 L per day for a family of five, was the daily requirement of drinking water. If they use a water filter 8 hr. a day, the required filter flow rate must be at least 1 L/hr. The CITE S1-CR team defined this as the lowest permissible flow-rate for a GNE filter and therefore its end-of-life.

The scoring for rating clean water production differed for each filter category, because their clean water flow rates were not comparable. The flow rate of a conventional particle removal filter was greater than 50 L per hour, while the flow rates of GNE filters were generally within the range of 1 to 10 L per hour. An RO filter had a flow rate of around 14 L per hour. The criteria for evaluating the clean water flow rate of the GNE filters, as defined by the S1-Consumer Reports team, are shown in Table 11.

Table 11. Criteria for Evaluating Clean Water Flow Rate of the GNE Filters

Performance	Clean Water Flow (L/hr.)
Excellent	8~10
Very Good	6~8
Good	4~6
Fair	2~4
Poor	0~2

RO Percent Recovery

Percent recovery is the amount of water that is being recovered as clean water as opposed to being discarded as wastewater (also known as "brine" or "concentrate").

The equation for percent recovery is as follows: $\% \, Recovery = \frac{Permeate \; Flow \; Rate}{Feed \; Flow \; Rate} \times 100$

RO water filters are known to create wastewater at rates that can exceed three times the amount of the clean water being produced (Eisenberg, T. N., 1986). This is a significant sustainability issue because a valuable natural resource is being wasted. However, if the percent recovery is too high for the RO system design, it can lead to significant problems due to scaling and biofouling. Additionally, it represents a significant operating cost for the homeowner if they have to pay for frequent RO membrane filter replacement parts.

Filter End-of-Life

Filter end-of-life measures how long a filter can retain its clean water flow rate. In this study, the end-of-life for GNE filters was defined as when the clean water flow rate fell below 1 L/hr, where initial flow rate fell between 1 L/hr and 10 L/hr. For RO filters, the end-of-life was defined as when the clean water flow rate fell below 100 mL/min, where initial flow rate was above 10 L/min. It is a factor related to the convenience of using the filter and the lifetime cost of the filter. Table 12 presents our evaluation criteria for the lifetime of GNE filters.

Table 12. Criteria for Evaluating GNE Filter Lifetime

Performance	Lifetime (days)
Excellent	24.75~31.25
Very Good	18.25~24.75
Good	11.75~18.25
Fair	5.25~11.75
Poor	0~5.25

It should be noted that, for the RO filters, due to time constraints, we were only able to perform end-of-life testing on one model each of two RO filters (Clean Water Dolphin RO and Tata Swach Platina RO).

TEST WATER SOURCE

Base Water

Base water is the water into which the contaminants, including turbidity, TDS, and *E. coli*, were added to form the "challenge water" that is used to test the filters in the lab. Thus, it needed to be consistent in this study and in any potential further research at MIT or in India. Various sources of water were available at the Consumer Reports lab that could be used as the base water: Yonkers' municipal water, Consumer Reports' well water, and deionized water.

Considering all the advantages and disadvantages of the three water sources, the team used the deionized water for most of the summer, because the initial plan was to measure *E. coli* removal rates throughout the lifetime of each filter. For this scenario, the *E. coli* bacteria would have been mixed into the water of one of the two available 100-gallon (378 L) tanks. However, such a lab setup had an associated high cost of buying phosphate buffered saline (PBS). After investigating substitutes for a saline solution in place of PBS, the team invented the "*E. coli* Injection System" to provide small batches of *E. coli* at the RO filter's inlet that did not require a long lifetime. The *E. coli* was only tested at the beginning and end-of-life for each filter. This process imitates the real condition of bacterial contamination, which often appears for a short period.

Challenge Test Water

Challenge test water is used to test water filters under the worst-case scenario. The WHO Protocol (WHO, 2014b) recommendations for challenge water concentrations are shown in Table 13.

Table 13. Challenge Test Water Characteristics (WHO, 2014b)

Constituent	Specification	Adjustment Materials
Turbidity (NTU)	40±10 NTU	ISO spec. 12103-A2 fine test dust
TDS (mg/L)	1500±150 mg/L	Sea Salts, Sigma Chemical Company (7732-18-5)

Deionized water is the base water in the WHO Scheme (WHO, 2014a). Turbidity and TDS are added to deionized water to form the WHO challenge water. The CITE team used ISO 12103-1/CD, A2 fine test dust from PTI (Powder Technology Inc.), the same test dust suggested by WHO, to create challenge water with a turbidity of around 40 NTU. (The specification for the A2 fine dust is shown in Appendix A.)

After a series of trial experiments, it was determined that 70 mg/L of test dust produced a turbidity of ~40 NTU. By using the tank's small circulating pump, the test dust was well dispersed throughout the 100-gallon tank within 10 min.

For TDS, we substituted Epsom salts (100% $MgSO_4$) for sea salts to provide TDS and hardness at the same time. It was determined that 4 g/L of Epsom salts produced a TDS of 1525 mg/L.

The challenge test water formulation for this study can be seen in Table 14.

Table 14. S1-Consumer Reports Team Challenge Test Water Formulation

Constituent	Specification	Adjustment Materials
Turbidity (NTU)	40±10 NTU	ISO spec. 12103-A2 fine test dust
TDS (mg/L)	1500±150 mg/L	Epsom Salts (100% $MgSO_4$)

***E. coli* Solution**

An *E. coli* solution was created to measure the filters' ability to remove bacteria. The challenge concentration of *E. coli* used by the CITE team was 10^5 MPN/100 mL, which is in line with concentration levels for challenge water as defined in the WHO Scheme (WHO, 2014b). A non-pathogenic K12 strain of *E. coli,* Product #10798, was purchased from the American Type Culture Collection (ATCC).

An amount of 0.5 mL of the freeze-dried *E .coli* was placed into 4.5 mL of K12 culture broth made up of 8 grams (g) of tryptone, 0.5 g of sodium chloride (NaCl), and 1 L of deionized water. This solution was then incubated for 8 hr. at 37°C. After 8 hr., the mixture was streaked onto Petri dishes using a sterilized mix-stick and incubated for another 8 hr. at 37°C. A colony from the plate was then placed into 10 mL of Luria Broth and incubated for 24 hr. The final concentration of *E. coli* was approximately 10^9 MPN/mL. After incubation, the solutions were placed in a refrigerator at 4°C. When refrigerated, this solution has a lifetime of approximately one month.

TEST METHODS

Turbidity Test Method

Turbidity was tested using the HACH 2100P turbidimeter, Product Number: 46500-00.[15] The turbidimeter was standardized using *StablCal® Calibration Set*. Procedure for measuring is as follows:

[15] https://www.hccfl.edu/media/186506/hach%20turbidimeter%202100p%20manual.pdf

1. More than 10ml of sample is collected in a 100 ml sterile sampling bag.
2. From that bag, it is is poured into the 15 ml glass vial taking care that the glass vial is not touched below 10ml line (oil from hands can distort the reading;
3. Vial is inserted into the turbidimeter and lid is closed;
4. “Read” button is pressed and the number in NTU is recorded in lab notebook; .

TDS Test Method

TDS was tested using the HACH Pocket Pro^{TM} Low Range TDS Tester (Product Number: 9531200) TDS meter.

The HACH low range TDS tester is for use with general water samples.

- For low range TDS, we performed 2-point calibration by doing calibration two times with different standards.

- The sensor cap was used as the sample/text vial, as recommend by the manufacturer. Because air bubbles under the sensor tip can cause slow stabilization or error in measurement, we gently shook the test until bubbles were removed.

***E. coli* Test Method**

In order to measure the concentration of *E. coli*, the team used the Quanti-Tray/2000 test method developed by IDEXX©. This involves a three-step process:

(1) Extract the treated water into a sterile 100 mL Quanti-Tray bottle. Dilute the effluent using deionized water to form a 100 mL sample mixture.

(2) Pour the 100 mL solution into a Quanti-Tray. Place the Quanti-Tray into the Quanti-Tray® Sealer 2X, which automatically distributes the sample mixture into separate wells.

(3) Place the sealed Quanti-Tray into a pre-heated 35°C incubator. After 24 hr., the number of positive wells can be converted to a Most Probable Number (MPN).

As shown in Figure 22 below, the total coliform is determined by counting the wells that turn yellow; the *E. coli* is calculated by counting the wells that both turn yellow and fluoresce.

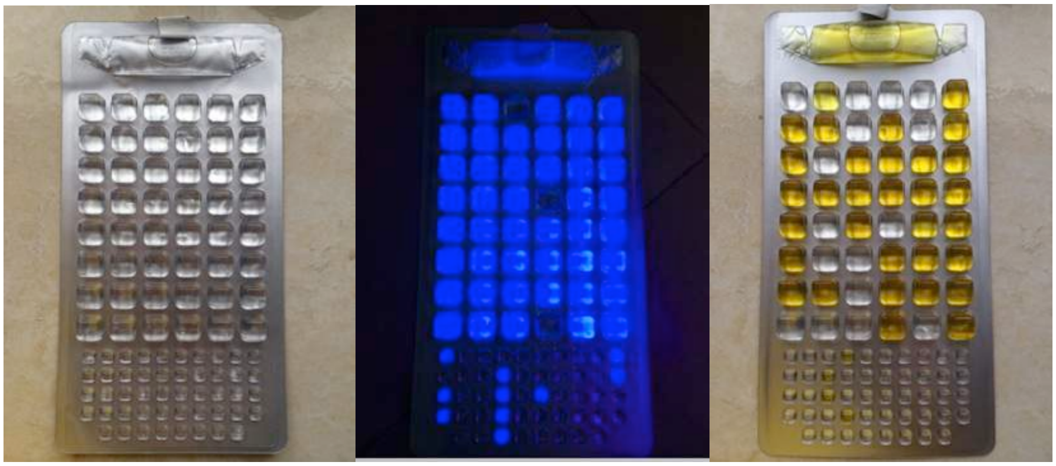

Figure 22. Method to Count Total Coliform and E. coli

Sterilization Procedures and Quality Control

It was imperative that all tests be kept as sterile as possible. Thus, all glassware was sterilized in an autoclave for 50 min. at 121°C and at high pressure (16 to 20 psi). All surfaces were also sterilized with 70% isopropyl alcohol before and after testing.

All bacteria tests were performed in triplicate, and the median value was used for LRV calculation. Distilled water was used for sample controls.

TEST SETUP

Plumbing Setup

The Consumer Reports plumbing setup developed by the team is shown in Figure 23. This test rig was designed to produce sufficient challenge test water for 24 hr. and to feed the reverse osmosis filters automatically.

The major plumbing parts include:

(1) Floor drains throughout the Consumer Reports lab.

(2) One deionizer that was used to produce the base water.

(3) Two 100-gallon plastic water tanks, which were used to make and store the challenge test water.

(4) One ¾ horsepower water pump paired with an 80-gallon pressurized tank and pressure controller.

(5) PVC piping to connect those parts mentioned above.

(All parts are listed in Appendix B.)

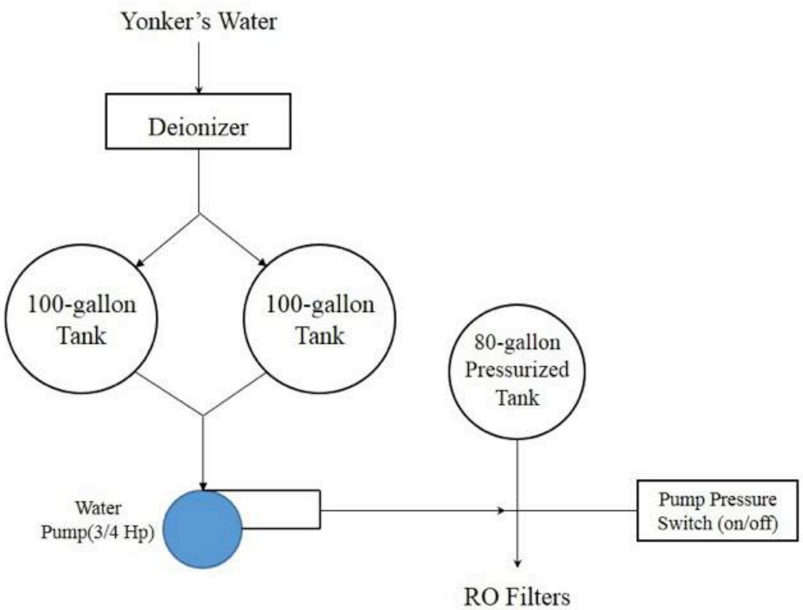

Figure 23. S1-Consumer Reports' Plumbing Setup

Reverse Osmosis (RO) Flow Test Rig Development

The Consumer Reports test rig was modified to meet the requirements of CITE's water filter evaluation. The new test rig used only one flow meter. However, each filter was subjected to a continuous flow of challenge water whether or not the flow rate was being measured. This greatly increased the testing speed of filter lifetime. The new test rig was also paired with LabView software to automate data processing and sequence valve openings and closings. Thus, the system was able to turn on/off solenoids automatically, and measure flow and pressure. The team tested two RO filters simultaneously by monitoring both clean water and wastewater flows.

Figure 24 shows a schematic of the new test rig used to evaluate a single RO filter. Two solenoids are provided to each filter flow. Four solenoids are required for these two flow paths if both clean water and wastewater flows are measured. Figures 25 and 26 show the modified rig.

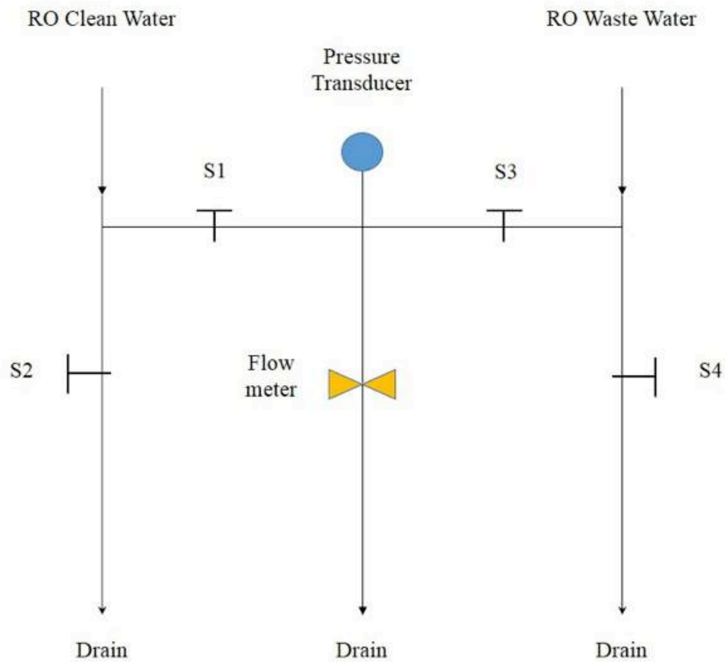

Figure 24. Single RO Flow Test Rig Schematic

Figure 25. Modified Test Rig

Figure 26. Modified Test Rig with Control Panel

The *E. coli* Injection System

E. coli removal was tested at the beginning and end of a filter's lifetime to avoid the prohibitive cost of ensuring that the *E. coli* lifetime was sufficiently long to be incorporated into the challenge water over the filter's lifetime. An *E. coli* Injection System was developed for the RO filters.

As seen in Figure 28, the *E. coli* injection rig included two major portions:

(1) One standard single cartridge filter used as the mixing vessel.

(2) One 6-gallon (23 L) pressurized tank. The water filter normally found in the cartridge was replaced with a perforated PVC pipe in order to mix the incoming water from the pump with the *E. coli* broth on its way to the pressure tank.

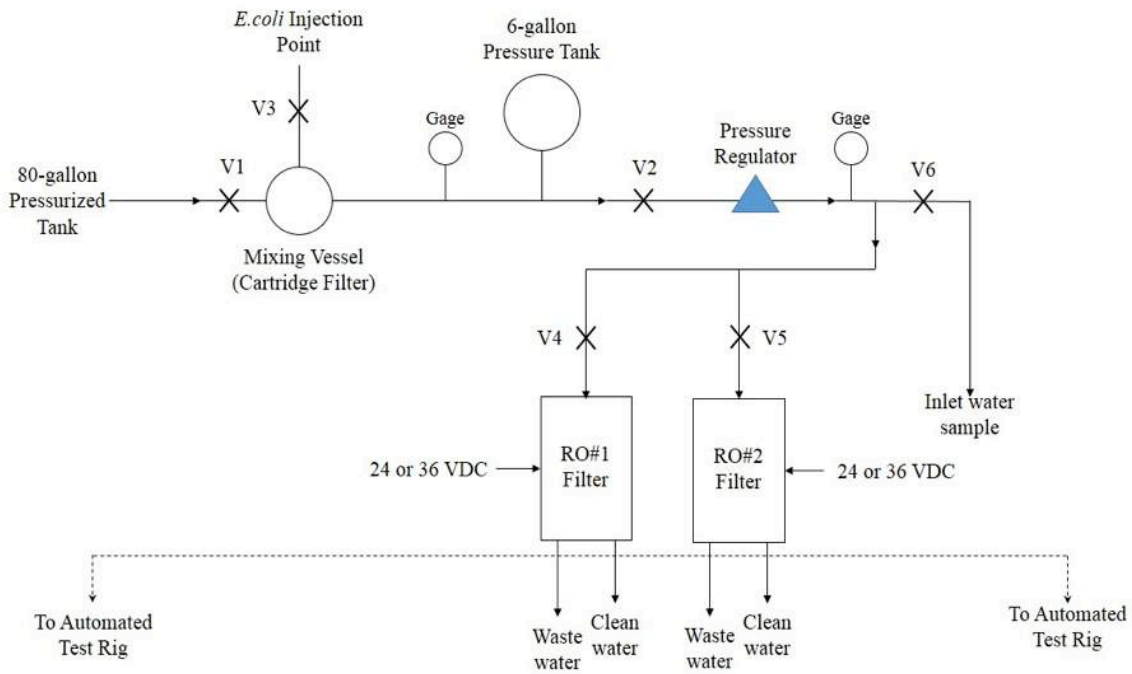

Figure 27. *E. coli* Injection Rig Schematic

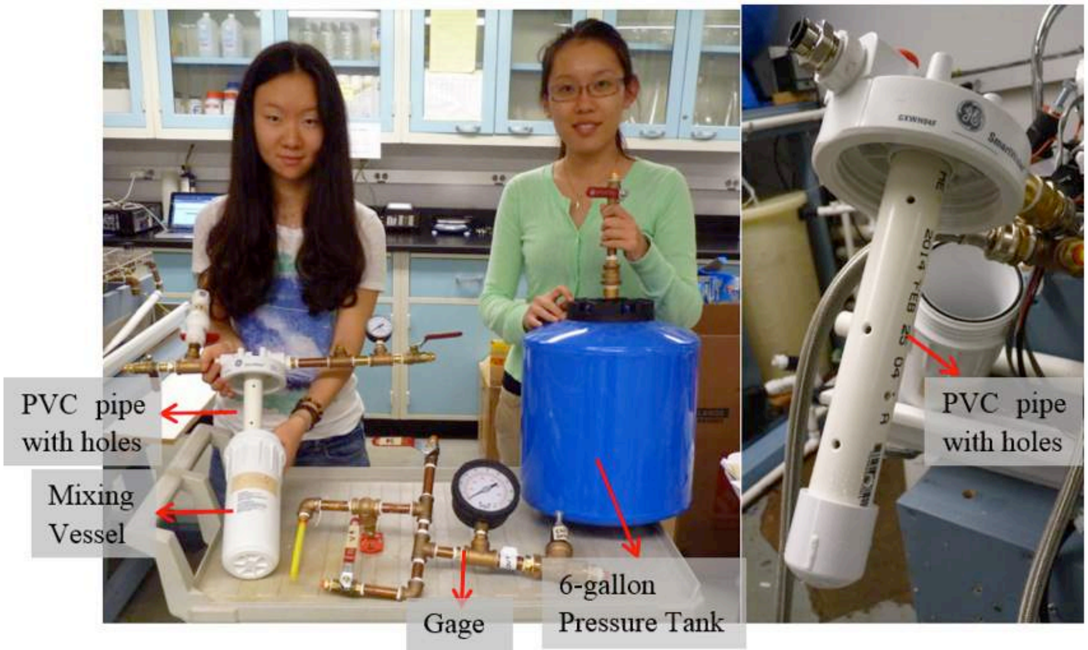

Figure 28. *E. coli* Injection Rig

Normal challenge test water is flushed through the plumbing system for about 5 min. The mixing vessel is opened and emptied. After it is closed, 1 L of *E. coli* broth at a concentration of 10^7 MPN/100 ml is poured into the mixing vessel through the *E. coli* injection point as shown in Figure 29. The valve (V3) is then closed when the vessel is filled with *E. coli* broth.

By opening the valve (V1), the challenge test water from the 80-gallon tank mixes with the *E. coli* broth. The six-gallon pressure tank then fills with this *E. coli* mixture, providing about 15 min. of continuous flow for testing one RO filter at a time.

The steps to conduct the *E. coli* injection test protocol are as follows:

(1) An *E. coli* solution of 10^7MPN/100mL is placed in a 2 L jar.

(2) The valve to the injection hardware and from the injection hardware to the RO inlet is closed. 1 L of E. *coli* broth is poured into the injection canister.

(3) Using deionized water as the source, at the peak water pump pressure of about 60 psi, the valve upstream from the injection system is opened. Water mixes with the broth as it flows into an empty six-gallon pressure tank. When the flow stops, the valve upstream of the injection system is closed to disconnect the water pump from the test rig.

(4) At this point, the test run begins with the valve downstream from the injection system being opened at time equals zero (T_0) and water flow to the RO begins.

(5) Samples are collected at the inlet, waste, and clean water drains to measure their *E. coli* concentration.

The *E. coli* injection rig has three major benefits:

(1) There is no need to use the expensive PBS buffer solution.

(2) Sterilization and cleanup are simplified since only a small amount of the plumbing is exposed to *E. coli*.

(3) The amount of *E. coli* required is drastically reduced.

TEST METHODS FOR EACH FILTER CATEGORY

Cloth and Mesh Filters Test Method

Turbidity removal: The S1-India field team found that Ahmedabad households use cloth filters in two ways: (1) tying the cloth filter directly onto the faucet, and (2) tying it onto a bucket and pouring in water. We used the second method to test the cloth filters. Whereas controlling water pressure would be possible with the first method, we couldn't make the water pressure constant with the second method. Because we assume that water pressure would significantly influence the turbidity removal, we choose the second method, which would give more variable turbidity removal results and better reflect the actual conditions.

Figure 29 shows the experimental setup for testing cloth and mesh.

Figure 29. Experimental Setup for Testing Cloth and Mesh

The test procedure for testing cloth involves six steps:

(1) Mark the 10 L line inside a 20 L plastic bucket.

(2) Tie the cloth onto the top of the bucket.

(3) Pour the challenge water onto the cloth until the water level in the bucket reaches the marked line.

(4) Remove the cloth and stir the filtered water in the bucket to ensure it is homogenous.

(5) Test the filtered water for turbidity. (See p. 34. Turbidity Test Method).

(6) Fold the cloth one, two, and four times; and test their turbidity removal, respectively.

The testing procedure for mesh filters is basically the same as that for cloth filters above. But because the mesh filters are manufactured and used as two-layer (see Figure 30 right), they were not tested up to 8 layers.

Cloth filter *E. coli* test method: The test procedure involves five steps:

(1) Tie the cloth onto a sterilized 800 milliliter (mL) bottle.

(2) Pour the 10^5MPN/100 mL *E. coli* solution onto the cloth so the outflow is collected in the sterilized bottle.

(3) Remove the outflow from the bottle.

(4) Test the *E. coli* concentration.

(5) Test the *E. coli* removal of one-layer, two-layer, four-layer, and eight-layer cloths, respectively.

Figure 30 shows the setup for the cloth *E. coli* test.

Figure 30. Experimental Setup for Cloth E. coli Test

Gravity Non-Electric (GNE) Filters Test Method

Flow rate, turbidity removal, and lifetime test method: Before testing, the filter must run properly. The procedure involves three steps:

(1) Check the manufacturer's instructions about the volume capacity of the top container. Define the container's full level and half-full level and mark them.

(2) Run one volume of deionized water through the GNE filter (the volume of the upper chamber of the given GNE filter determines that volume). Note: If the manufacturer indicates another "break-in" method, this should be followed.

(3) Empty the filter completely, including any parts and the bottom of the filter where the tap is located. Close the filter's tap.

After accomplishing the above steps, testing begins. Because the tap of each filter is not installed exactly at the bottom of the storage container, a small volume of water is always stored in the filter safe storage container. Thus, some amount of water must be filtered before the clean water leaves the tap. The following seven-step procedure addresses this issue:

(1) Take three samples of the challenge test water for each test and check their turbidity.

(2) Fill the filter to its half-full level with the challenge test water and open the tap.

(3) Start the timer once the clean water starts coming out of the tap.

(4) To compensate for the water stored in the filter, immediately fill the water to the half-full level in the filter and document this amount of water on the data sheet.

(5) Collect the outflow using a bottle with a volume of about 800 mL.

(6) When clean water in the bottle reaches 400 mL, stop the timer, calculate the flow rate, and test the turbidity.

(7) Refill the filter to its full capacity and let the water flow from the tap until the filter is empty.

For subsequent tests, the procedure is simplified:

(1) Take three samples of the challenge test water for each test and check their turbidity.

(2) Fill the filter to its half-full level with the challenge water and open the tap.

(3) Once the filter starts to produce outflow, start the timer and collect the outflow using a bottle with a volume of about 800 mL.

(4) When clean water in the bottle reaches 400 mL, stop the timer, calculate the flow rate, and test the turbidity. Document the total volume of test water that has been filtered.

(5) Refill the filter to its full capacity and let the water flow from the faucet until the filter is empty.

(6) With every second refill of the filter (i.e., 3rd, 5th, 7th, etc.), repeat the above steps until the flow rate of clean water from the filter is below 1 L per hr. At this point, the filter clogs and the documented total volume of water filtered is its lifespan.

E. coli **removal test method:** The S1-Consumer Reports team monitored *E .coli* removal at the beginning and end of the filter's life. The filters were half-filled with the 10^5MPN/100 mL *E. coli* solution. Three outflow samples were collected, and the *E. coli* concentration was tested using the IDEXX Quanti-tray method.

Reverse Osmosis (RO) Filters Test Method

Flow rate, turbidity removal, TDS removal, and lifetime test method: The flow rate of RO filters was monitored and recorded by the Consumer Reports-V2.0 test rig. Turbidity and TDS removal were measured at the beginning, middle, and end-of-life of each RO filter for its inlet, clean water, and wastewater, respectively. When the flow rate dropped to less than half of the initial flow rate, that level was defined as the filter's end-of-life. Once the RO filter's flow rate started to decrease, it fell rapidly (in 4 to 5 hr.) to below 80 ml/min, which was not detectable by the flow meter.

E. coli **removal test method:** It proved difficult to provide a consistent and stable level of *E. coli* introduced into the RO filters. The *E. coli* injection process described in Section 4.4.3 gives a continual dilution of the initial, concentrated *E. coli* broth. A well-functioning RO membrane should have no *E. coli* in the clean water flow. To measure the exact *E. coli* removal rate, the peak *E. coli* at the inlet must be measured. This requires taking many water samples at the inlet.

For instance, Figure 31 illustrates the expected *E. coli* concentration for inlet, wastewater, and clean water versus time, assuming that the pre-filters before the RO membrane do not remove *E. coli*.

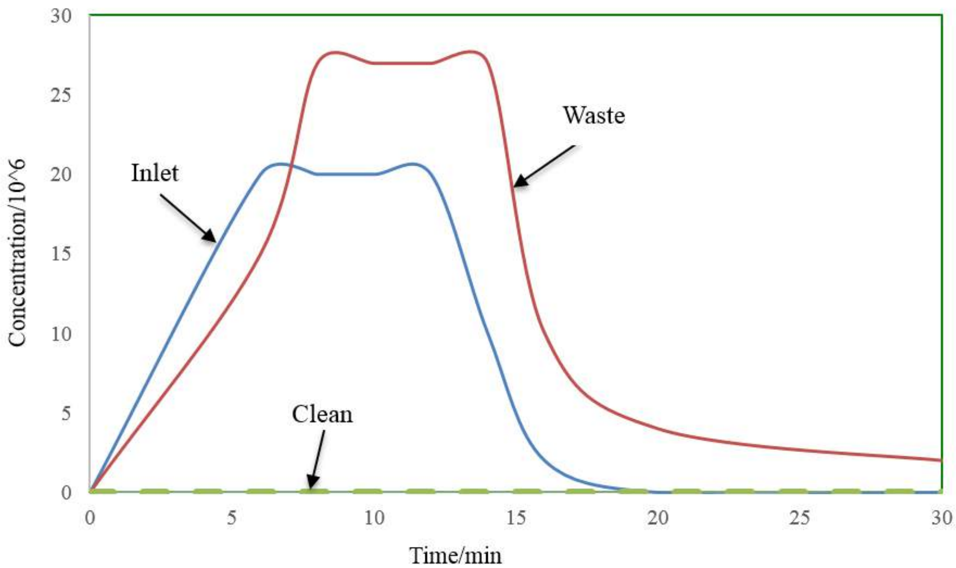

Figure 31. Depiction of E. coli Concentration for Inlet, Waste, and Clean Water vs. Time

The blue line indicates the inlet *E. coli* concentration. Based on testing, the inlet *E. coli* concentration is expected to reach its peak value at around 6 min., and then remain at this peak value for another 6 min. when simultaneously testing with two RO filters in parallel.

After about 12 min., the water pressure of the six-gallon small pressure tank dropped from 60 psi to 20 psi and ended the test. At that point, the valve from the pump was opened and deionized water flowed in. There was a delay time of approximately 2 min. for the inlet water to arrive at the RO membrane; thus, the *E. coli* concentration of the wastewater reached its peak 2 min. later. So long as the RO membrane was not broken, the *E. coli* concentration of the clean water downstream from it was always expected to be zero. The RO membrane has a pore size much smaller than the size of *E. coli*, and thus provided a good barrier to intercept the *E. coli*.

Only one RO filter was run at a time to maximize the time period that the *E. coli* stream was able to stay at a constant delivery pressure of 15 psi.

The procedure is given below. Please refer to the Figure 27 to better understand the sequence of valve closing and opening.

(1) Empty the mixing cartridge for the *E. coli* and the 6-gallon (23 L) pressure storage tank. Close off the gate valve from the drain water vessel receiving the inlet/clean/waste/water lines. Place some dilute bleach in the drain of the water vessel.

(2) Close valves V1, V2, V4, V5, and V6; open valve V3.

(3) Pour about 1 L of the *E. coli* broth that has a concentration of around 10^9 MPN/100 ml through a small funnel into the open valve. Close valve V3. Clean funnel and valve with alcohol.

(4) Run water pump until it reaches its peak pressure of about 60 psi.

(5) Open valve V1 until the pressure of the 6-gallon pressure storage tank also reaches 60 psi, and then close valve V1. Clean off the end of the inlet/clean/waste lines with alcohol.

(6) Turn on the power for the RO filters' pump and solenoids in RO #1 and #2. Open the automated test rig control interface where a diagram of the solenoids is shown. Click to "open" solenoids 2, 4, 6, and 8.

(7) Start the test (Time=0): Either valve V4 or V5 is opened depending on which RO filter is being tested. Then open valve V2 and stabilize the pressure regulator at 15 psi.

(8) Refer to Table 4-11 below for an example of the sampling timeline.

(9) After collecting all the water samples, continue to take flow data using the automated test rig.

(10) When the test of flow in Step #9 is complete, shut down the RO filters' pump and solenoids.

(11) Open the water valve for draining the water vessel. Clean up carefully using the spray bleach container to remove the *E. coli*. Clean carefully and flush the entrance to valve V3 where the concentrated *E. coli* broth was inserted into the injection hardware.

Ensure that the temporary storage container, where the RO's clean and wastewater drain tubes empty, is open to the floor drain. Clean up carefully with the spray bleach container to remove *E. coli*. Clean carefully and flush the entrance to valve V3, where the concentrated *E. coli* broth was inserted into the injection hardware.

	Time	Dilution Ratio 1	Dilution Ratio 2
Inlet	6min 10min 14min 18min 21min 36min	$1:10^3$ $1:10^3$ $1:10^3$ 1:10 1:10 1:1	$1:10^5$ $1:10^5$ $1:10^5$ $1:10^3$ $1:10^3$ 1:100
Waste	0min 7min 11min 15min 20min 25min 40min	1:1 $1:10^3$ $1:10^3$ $1:10^3$ 1:10 1:10 1:1	- $1:10^5$ $1:10^5$ $1:10^5$ $1:10^3$ $1:10^3$ -
Clean	0min 12min 16min 24min	1:1 1:1 1:1 1:1	- - - -

Table 15. Sampling Timeline and Dilutions for RO E. coli Test

Test Results

Cloth and Mesh Water Filters

Cloth

One of the important results of the cloth and mesh filter testing is the micrograph of the different cloth and mesh products described earlier.

Only the “best quality,” Cloth #1, restricted the flow of water. Even with eight layers of Cloths #2 and #3, the water went through the cloth as quickly as it could be poured. With eight layers of Cloth #1, the flow rate was 50 L/hr., which was extremely high compared to the GNE filters and the RO filters, which had flow rates ranging from 0.6 L/hr. to 4 L/hr. (GNE) and about 14 L/hr. (RO).

According to Figure 32 below, for Cloth #1, the turbidity removal and *E. coli* LRV both increased with the increase in the number of cloth layers. When tested as one layer or two layers, it was only able to remove less than 20% of the turbidity; normally, one would hope to attain at least 99% removal. When Cloth #1 is folded in 4 layers and 8 layers, it can remove 50% to 60% of the turbidity, respectively; the *E. coli* LRV was around 0.1 to 0.12, which means it can only remove 20% of the bacteria, an unacceptable performance as per CITE’s defined standard.

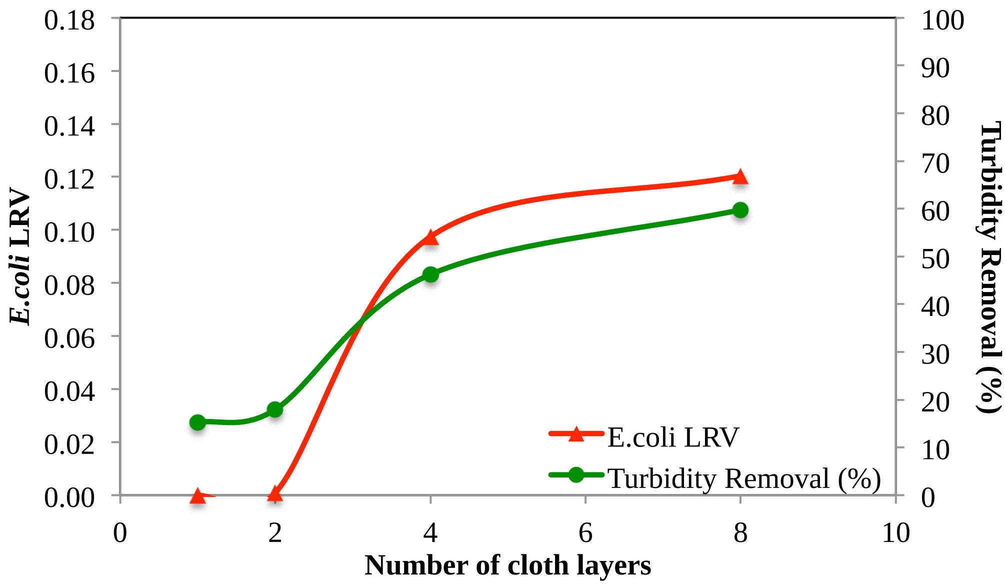

Figure 32. Cloth #1 E. coli LRV and Turbidity Removal vs. Number of Cloth Layers

Figure 33 shows the *E. coli* LRV and turbidity removal (%) of eight layers of Cloths #1, #2, and #3. Cloth #2 and Cloth #3 both had a lower removal than Cloth #1.

In general, eight layers of cloth can remove 20% to 60% of turbidity, but can significantly remove *E. coli*.

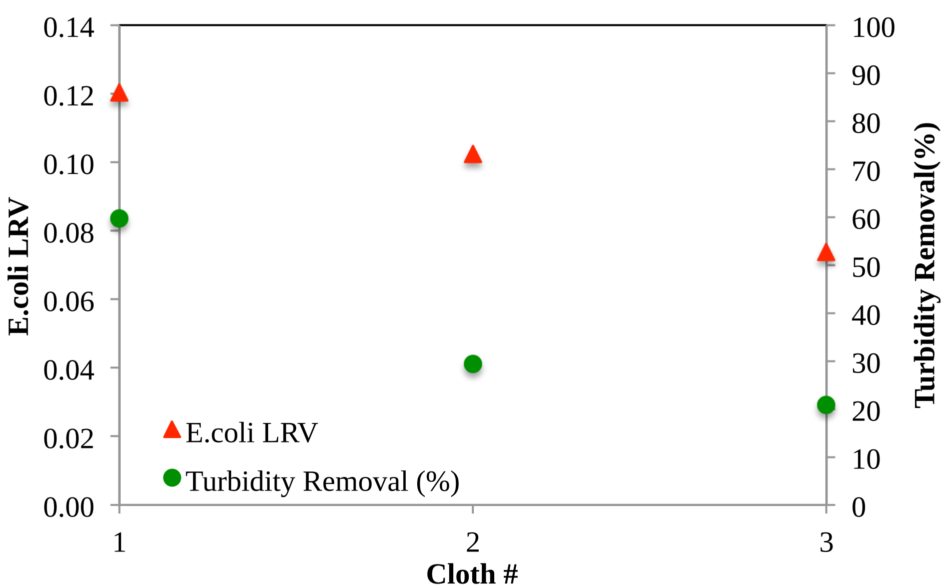

Figure 33. *E. coli* LRV and Turbidity Removal of Eight Layers for Cloths #1, #2, and #3

The challenge water went through the mesh as fast as it was poured. Turbidity removal was only

5% with a two-layer mesh.

GRAVITY NON-ELECTRIC (GNE) WATER FILTERS

The performance of the GNE filters is presented using the test attributes of: flow rate, *E. coli* LRV, and turbidity removal versus the volume of water passing through the filter. The turbidity removal is given as the percent of reduction. The *E. coli* removal is presented as the *E. coli* LRV. When the *E. coli* LRV is higher than four, the result is presented as "4" in the figures. In such cases, that filter is considered as "highly protective" for its ability to remove bacteria (WHO, 2014a), and as "excellent" in the Consumer Reports-defined standard.

Expresso Water Filter

As seen in Figure 34, except for a very short period at the beginning, the Expresso stainless steel water container flow rate was below 1 L/hr., the team's cutoff for end-of-life. The instructions indicated that the flow rate would increase after 15 days of use, but it remained well under 1 L/hr. and continued to decrease. To confirm the Expresso's low flow rate, a second sample was tested after being soaked in clean water for two days. This time, the initial flow rate never made it above 1 L/hr.

However, the Expresso had excellent turbidity reduction and *E. coli* removal. The turbidity removal remained at above 97%, and it can remove more than 99.99% *E. coli*.

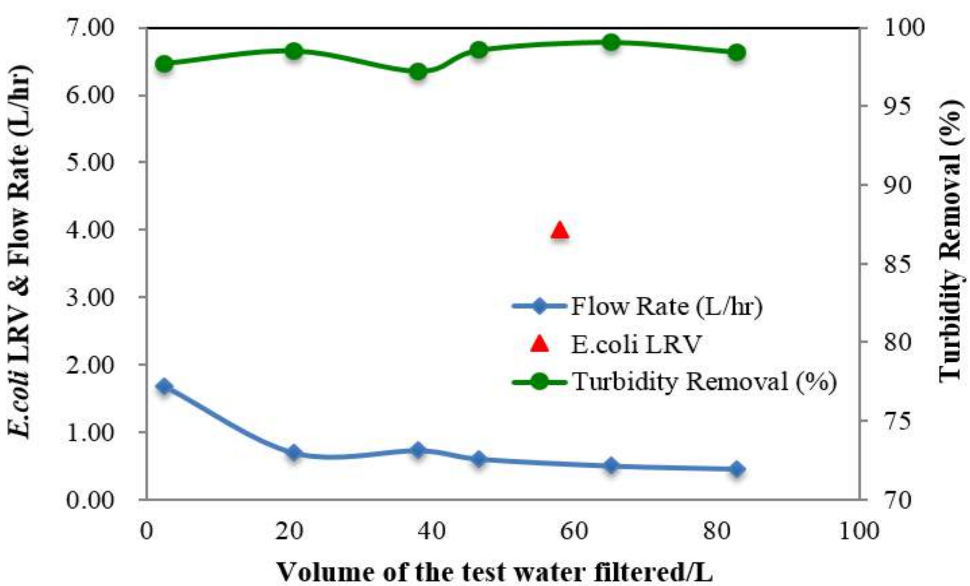

Figure 34. Expresso Water Filter Test Results

Tata Swach Cristella Plus

Figure 35 shows the test results for the Tata Swach Cristella Plus. The flow rates remained high and only decreased gradually after filtering more than 150 L of challenge water. After filtering 410 L of water, the flow rate was still higher than 4 L/hr. However, the turbidity and *E. coli* removal was much lower compared to other models. The *E. coli* LRV ranged from 1.5 to 2.0, meaning that it can only remove 95% to 99% of bacteria. The turbidity reduction fluctuated and was generally within the range of 70% to 85%.

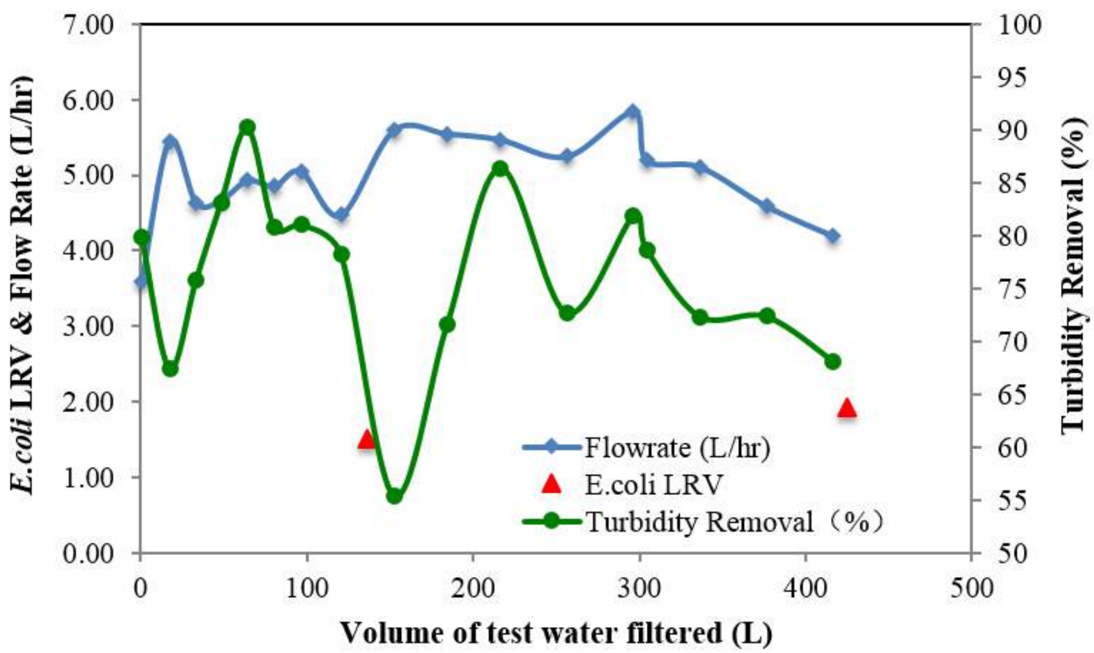

Figure 35. Tata Swach Cristella Plus Test Results

Tata Swach Smart 1500 L

Figure 36 indicates that the Tata Swach Smart 1500 L still has a fairly fast flow rate of 2.0 L/hr. after filtering 380 L of challenge water. Its predicted lifespan is 486 L of challenge water, which might be due to the high concentration of the challenge water used. If the feed water has a lower level of turbidity, the filter's lifetime should be longer. The highest flow rate was about 6 L/hr. But, its turbidity removal fluctuated considerably from 84% to 95%. Its *E. coli* LRV was also relatively low, remaining at about 2, which means that it removes 99% of bacteria ("poor" to "fair").

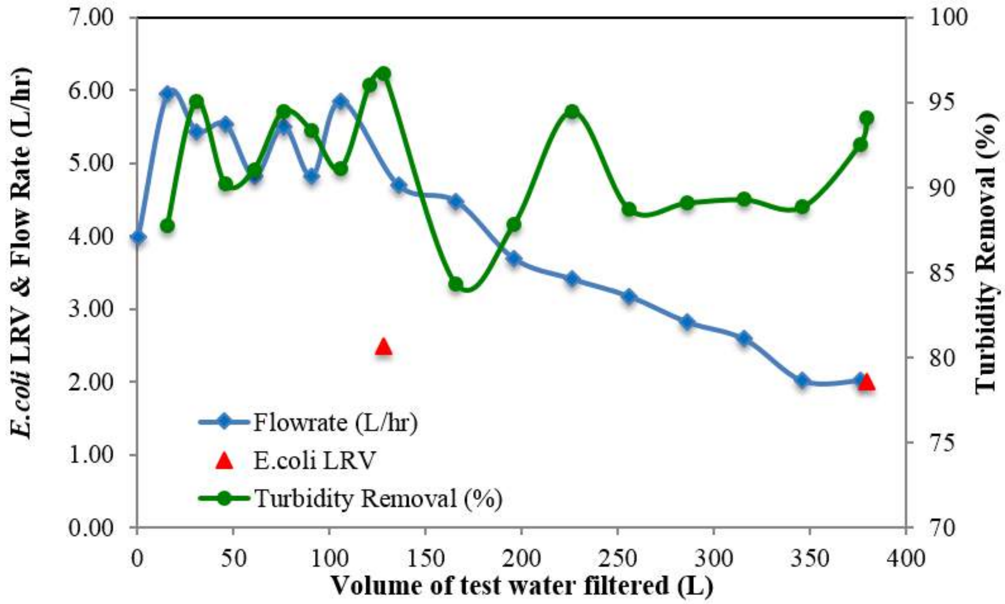

Figure 36. Tata Swach Smart 1500 L Test Results

Tata Swach Smart 3000 L

The only difference between the Tata Swach Smart 1500 and 3000 L models is the type of Tata filtration bulb used. The highest flow rate of the Smart 3000 L was 3.6 L/hr., which was lower than the highest flow rate of the Smart 1500 L, which was 6.3 L/hr. The lifespan of the Smart 3000 L was 220 L of water, which was shorter than the liters of water for Smart 1500 L. This might be because the Smart 3000 L performed better in removing turbidity, so it clogged much faster under such high-concentration challenge water. The *E. coli* LRV for both models was “protective” at around 2.5, according to WHO terminology, and “fair” based on Consumer Reports terminology.

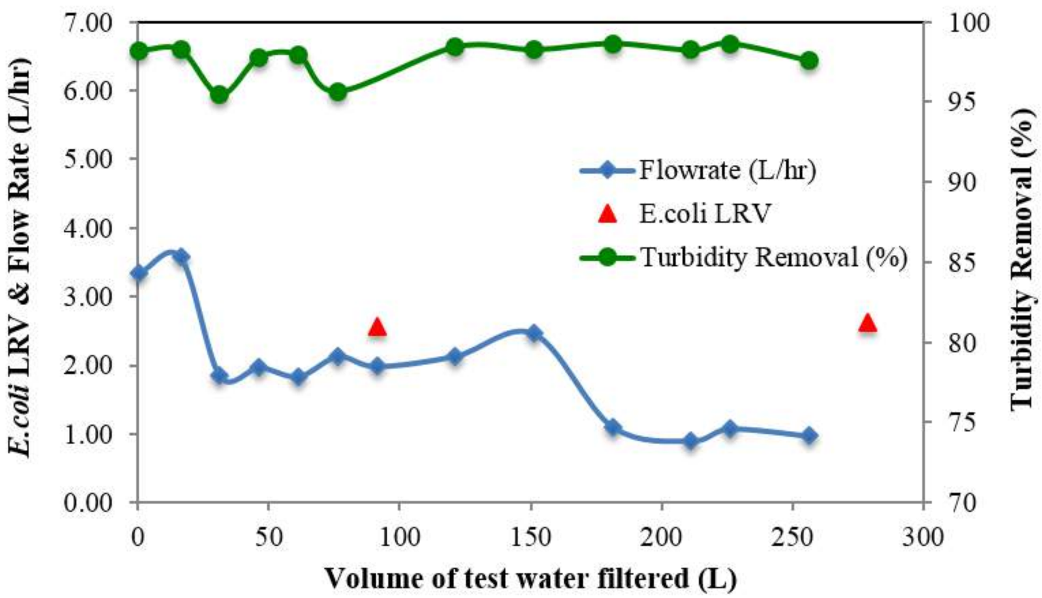

Figure 37. Tata Swach Smart 3000 L Test Results

Hindustan Unilever PureIt Classic 14L

The PureIt Classic 14L is a multi-stage filter. Its design showed a significant disadvantage in testing. The water first goes through a "Micro Fiber Mesh" to remove visible dust. Then it passes through a unique "Compact Carbon Trap" that removes dirt, parasites, and pesticide residuals. Next, a "Germkill Processor" kills almost all bacteria and viruses. Finally, the water goes through a uniquely designed "Polisher" to remove residual chlorine.

Due to the multi-stages, this filter could not provide a continuous clean flow. To confirm this performance problem, a second sample of the PureIt was tested. The results are shown in Figure 39 and Figure 40. Both samples clogged quickly. The first fell below 1 L/hr. after filtering 60 L of water and the second one only after 30 L of water.

The turbidity removal remained above 98% for both samples, and the *E. coli* removal remained higher than 99.99%, so it had "good" *E. coli* removal.

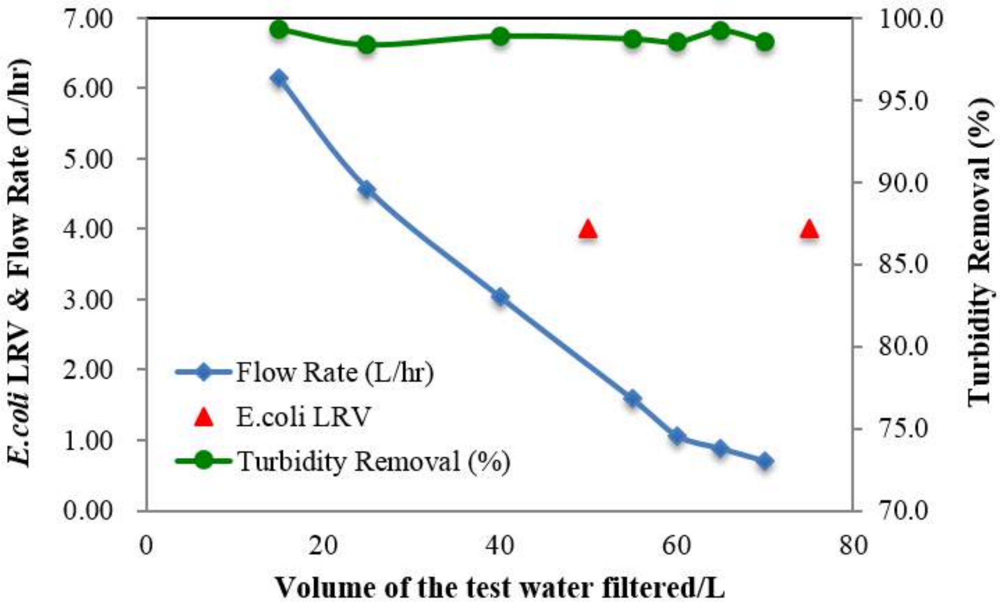

Figure 38. Hindustan Unilever's PureIt Classic 14L Test Results of Sample 1

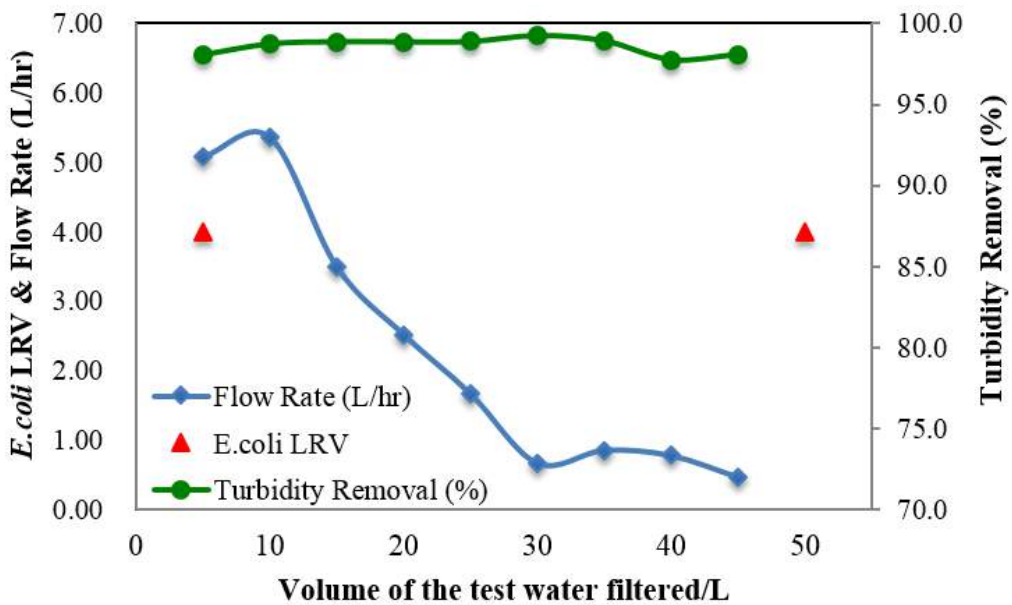

Figure 39. Hindustan Unilever's PureIt Classic 14L Test Results of Sample 2

Prestige LifeStraw

Figure 40 shows that the Prestige LifeStraw has a disappointingly short lifetime. It had a sharp drop-off of clean water production after filtering only 40 L of water. Its highest flow rate was relatively low at 1.9 L/hr. Nevertheless, it had an excellent turbidity removal above 97.9%; and, at 4 LRV (99.99%), its *E. coli* removal was “good.”

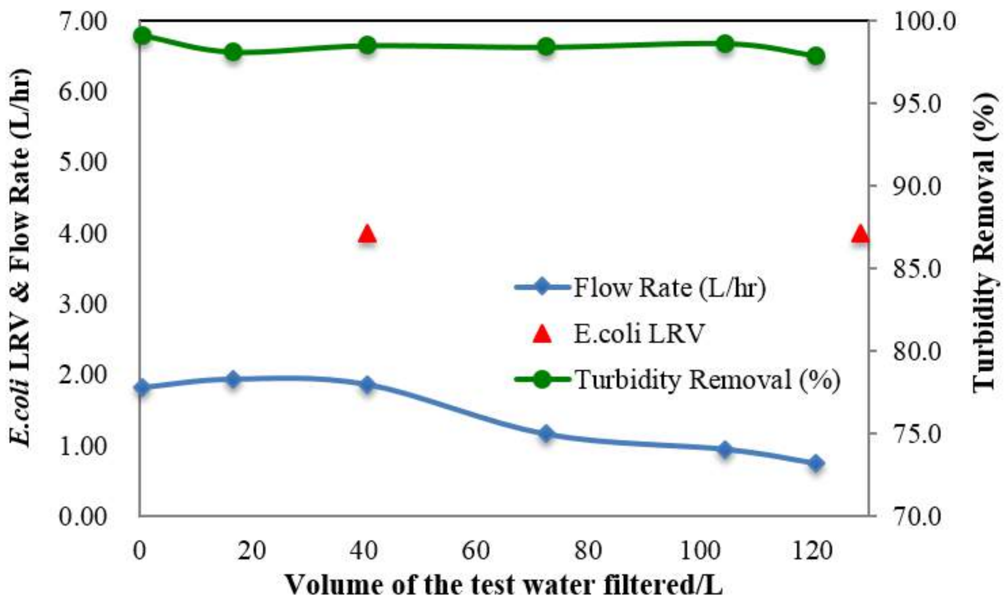

Figure 40. Prestige’s LifeStraw Test Results

Eureka Forbes AquaSure Amrit with Kitanu Magnet

The Amrit had one of the highest initial flow rates of 11 L/hr., but it dropped off quickly within the first 40 L of clean water production. After filtering 108 L of challenge water, the flow rate was still 1.54 L/hr. The lifespan—and the flow testing—was predicted to terminate at 117 L. The turbidity removal was excellent at around 99%. In the middle of its life, the AquaSure filter removed 99.9% of *E. coli*. Near its end-of-life, it removed 99.99% of *E. coli*, which is “good.” Overall, the AquaSure model did well in all three performance categories.

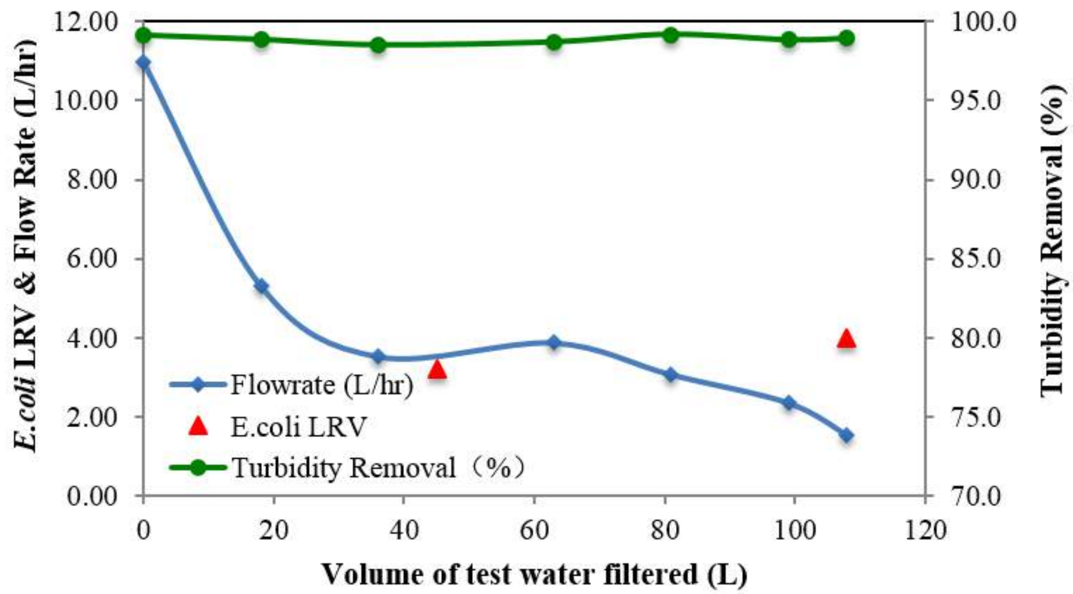

Figure 41. Eureka Forbes' AquaSure Amrit with Kitanu Magnet Test Results

KENT Gold UF Membrane Filter

The instructions for the KENT Gold claimed that this filter had a capacity of 10 L in the upper storage tank. In reality, it only contains 7 L. Additionally, its upper pre-filter has a very slow filtering rate, so it was difficult to add more than 5 L of water to this filter at one time.

Thus, the test method for this filter was changed to add 5 L of challenge water each time, and the flow rates were tested where 2.5 L of water was added per the test method.

As seen in Figure 42 below, the filter's highest flow rate was 5.7 L/hr.; it clogged after filtering about 55 L of challenge water. The turbidity removal, between 97% and 99.5%, was "good"; the *E. coli* was greater than 4 LRV for a removal rate of at least 99.99% of bacteria, which is also "good."

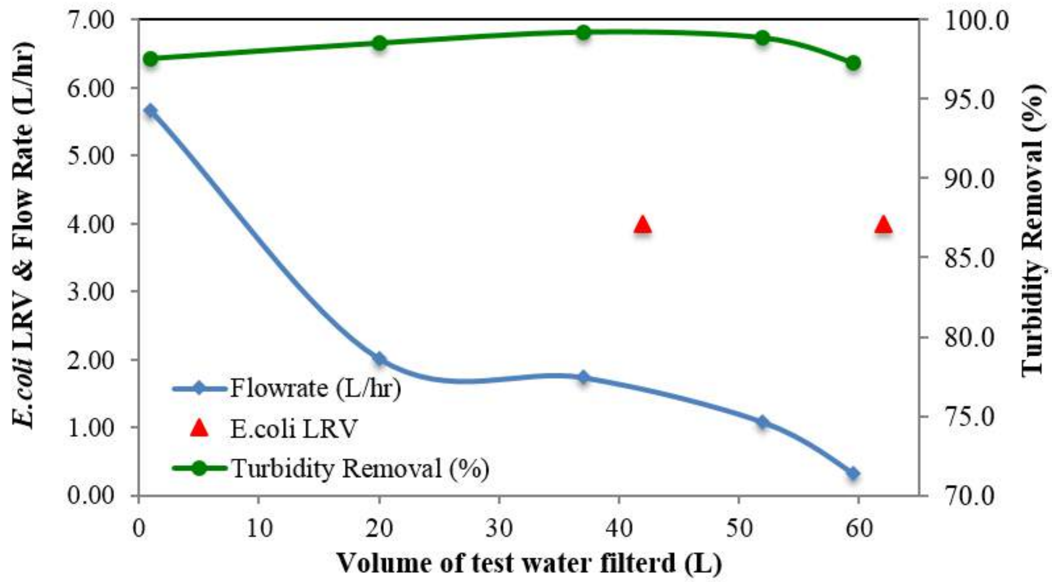

Figure 42. KENT's Gold UF Membrane Filter Test Results

Summary of GNE Filter Performance

GNE filters generally outperform cloth and mesh filters. However, they differ significantly in these attributes: flow rate, turbidity removal, lifespan, and *E. coli* removal. In general, the higher the flow rate, the lower the turbidity removal and the lower the *E. coli* removal.

Five models were able to remove higher than 95% turbidity during their lifetime. Three models can remove higher than 99.99% *E. coli*, which is "good," while the other four can remove higher than 99% ("fair").

Reverse Osmosis (RO) Water Filters

RO Turbidity and TDS Reduction

The turbidity and TDS reduction of the two RO filters (branded and locally assembled Dolphin models) were monitored at their beginning and end of life.

As shown in Table 17, both RO filters have excellent performance, almost 100%, in removing turbidity and TDS. As a consequence, the wastewater flow contained TDS at significantly higher, concentrated levels. "Clean % removal" refers to the percent reduction of turbidity (or TDS) in the clean water compared to that in the inlet. "Waste % removal" refers to the percent reduction of turbidity (or TDS) in the wastewater compared to that in the inlet.

Table 16. RO Turbidity and TDS Removal Results

Model Name	Time	<<<< Turbidity Removal >>>>					<<<< TDS Removal >>>>				
		Inlet (NTU)	Clean (NTU)	Clean % removal	Waste (NTU)	Waste % removal	Inlet (mg/L)	Clean (mg/L)	Clean % removal (%)	Waste (mg/L)	Waste % removal
Tata Swach Platina	10 hr.	37.7	0.19	99.5%	0.96	97.5%	1670	30	98.2%	2686	-60.8%
	End-of-life			99.5%					98.7%		
Clean Water Dolphin	10 hr.	37.7	0.18	99.6%	2.09	95.5%	1670	18	98.9%	2520	-60.5%
	End-of-life			99.7%					99.7%		
Dolphin Gold	<10 hr.	46	0.99	97.8%	4.33	90.6%	1570	46	97.1%	2580	-64.3%

RO *E. coli* Removal

Similarly, both RO filters were “excellent” in *E. coli* removal.

As seen in Figure 43 and Table 17, the *E. coli* concentration at the inlet of the Clean Water RO filter is much higher than that from the wastewater for the time period of 6 to 14 min. This verifies that the pre-filters of the Clean Water filter may have removed bacteria. Thus, when this filter’s water enters the RO membrane, its *E. coli* concentration has already been reduced significantly. In general, the Clean Water Dolphin RO had a clean water LRV as high as six, which is two LRV’s greater than WHO’s “highly protective” category. Hence, this is “excellent” *E. coli* removal performance.

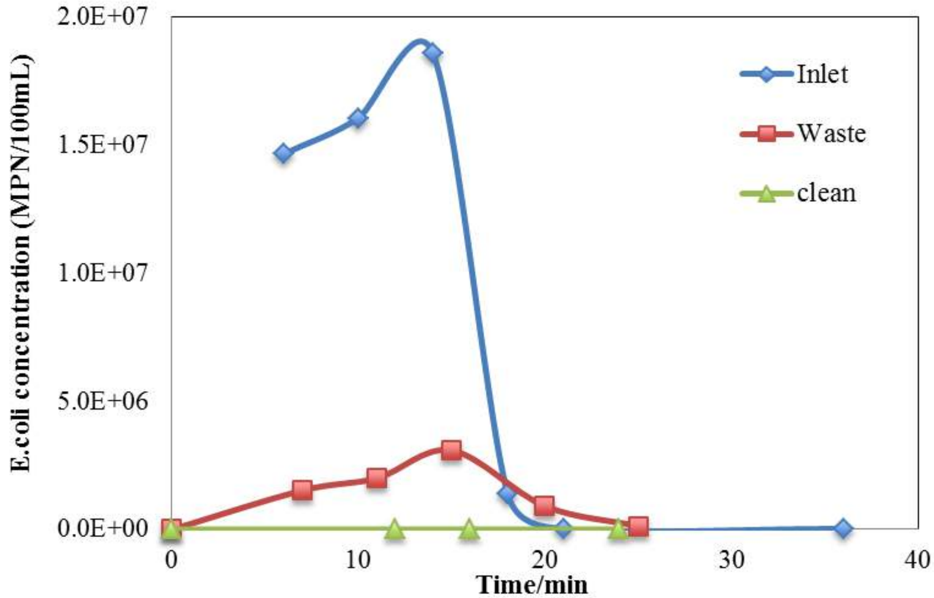

Figure 43. *E. coli* Removal Results for Clean Water (non-branded Dolphin RO type) Filter

Table 17. *E. coli* Removal Results for Clean Water (non-branded Dolphin RO type) Filter

Sample	**Time**	**Dilution Ratio 1**	**Result (MPN/100 mL)**	**Dilution Ratio 2**	**Result (MPN/100 mL)**	**Average**
Inlet	6 min.	$1{:}10^3$	$>2.4\times10^6$	$1{:}10^5$	1.5×10^7	1.5×10^7
	10 min.	$1{:}10^3$	$>2.4\times10^6$	$1{:}10^5$	1.6×10^7	1.6×10^7
	14 min.	$1{:}10^3$	$>2.4\times10^6$	$1{:}10^5$	1.9×10^7	1.9×10^7
	18 min.	1:10	$>2.4\times10^4$	$1{:}10^3$	1.4×10^6	1.4×10^6
	21 min.	1:10	1.5×10^4	$1{:}10^3$	2.4×10^4	2.0×10^4
	36 min.	1:1	$>2.4\times10^3$	1:100	2.9×10^4	2.9×10^4
Waste	0 min.	1:1	0	-	-	0
	7 min.	$1{:}10^3$	1.3×10^6	$1{:}10^5$	1.8×10^6	$1.51.3\times10^5$
	11 min.	$1{:}10^3$	2.0×10^6	$1{:}10^5$	2.0×10^6	2.0×10^6
	15 min.	$1{:}10^3$	$>2.4\times10^6$	$1{:}10^5$	3.1×10^6	3.1×10^6
	20 min.	1:10	8.5×10^5	$1{:}10^3$	9.8×10^5	9.1×10^5
	25 min.	1:10	$>2.4\times10^4$	$1{:}10^3$	1.3×10^5	1.3×10^5

	40 min.	1:1	$>2.4\times10^{3}$	-	-	-
Clean	0 min.	1:1	0	-	-	0
	12 min.	1:1	0	-	-	0
	16 min.	1:1	0	-	-	0
	24 min.	1:1	0	-	-	0

Table 18 below shows the *E. coli* results for the Tata Swach Platina RO filter. The same testing method was used here as above for the Clean Water Dolphin filter. The *E. coli* concentration did not reach its peak at 6 min., which may be due to the filter having a higher flow resistance at this time. Thus, its flow rate is lower when compared with the Clean Water Dolphin. Also unexpected was that the wastewater had *E. coli* higher than 2419.6MPN/100 mL, the limit of detection of an undiluted sample. This may mean that the silver impregnated pre-filter had removed bacteria. Although the team was not able to measure the *E. coli* concentration in the wastewater, these results indicate that the clean water LRV of the Tata Swach Platina is as high as six ("excellent" as defined by the Consumer Reports team). This is similar to the results found for the non-branded, Clean Water Dolphin RO filter.

Table 18. *E. coli* Removal Results for Tata Swach Platina Silver (branded RO type) Filter

Sample	**Time**	**Dilution Ratio 1**	**Result (MPN/100 mL)**	**Dilution Ratio 2**	**Result (MPN/100 mL)**
Inlet	6 min.	$1:10^{3}$	2.0×10^{4}	$1:10^{5}$	-
	10 min.	$1:10^{3}$	$>2.4\times10^{6}$	$1:10^{5}$	3.6×10^{6}
Waste	0 min.	1:1	0	-	-
	14 min.	1:1	$>2.4\times10^{3}$	-	-
	18 min.	1:1	$>2.4\times10^{3}$	-	-
Clean	0 min.	1:1	0	-	-
	15 min.	1:1	0	-	-
	19 min.	1:1	0	-	-

RO Flow Test and Lifetime/Clogging Results

Figure 44 below shows the flow and end-of-life test results for the Clean Water Dolphin RO filter. Its end-of-life occurred at 2750 min. (45.8 hr.) when the clean water production became less than 100 mL/min. At this point, it had been tested for over 54 hr. The clean flow showed a significant fall-off after which the waste flow also decreased. It is likely that the high level of test dust that created the artificial turbidity for the testing was filtered and accumulated in the cartridges, resulting in an increase in the filter's flow resistance.

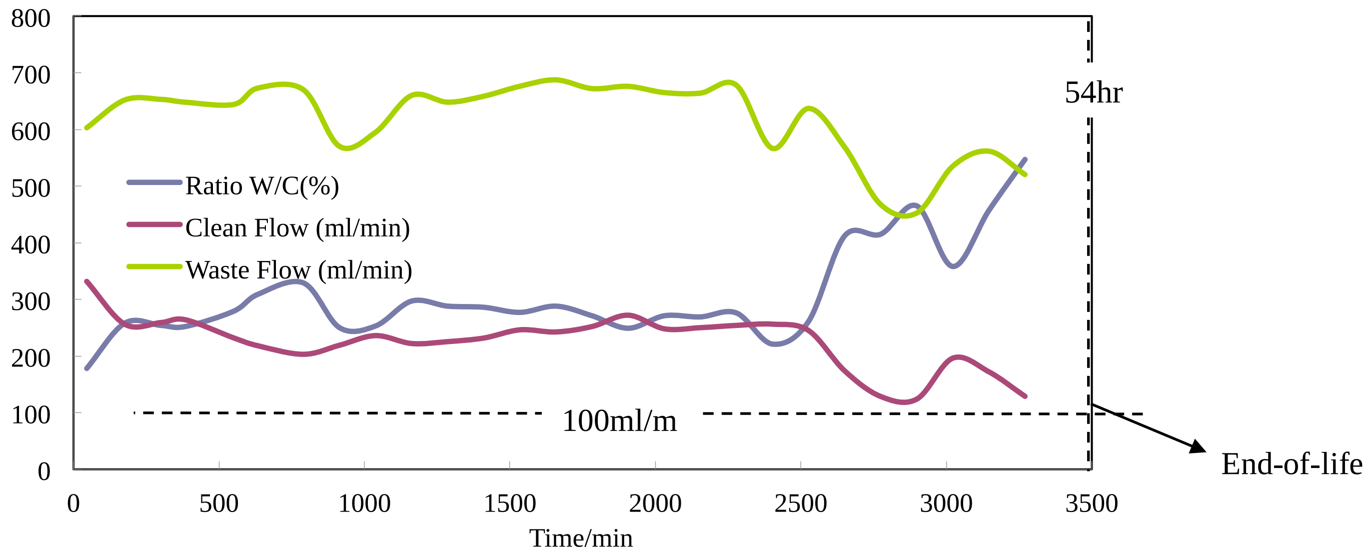

Figure 44. Clean Water (non-branded Dolphin RO type) Filter Flow Performance

As seen in Figure 45, the Tata Swach Platina had a significantly shorter life compared with the Clean Water Dolphin model. This filter showed a major reduction in clean water production at approximately 1700 min. (29 hr.) after filtering around 1450 L of challenge water, in contrast to the Clean Water Dolphin model, which had a lifetime of 2750 min. The flow rate of the wastewater also showed the same trend.

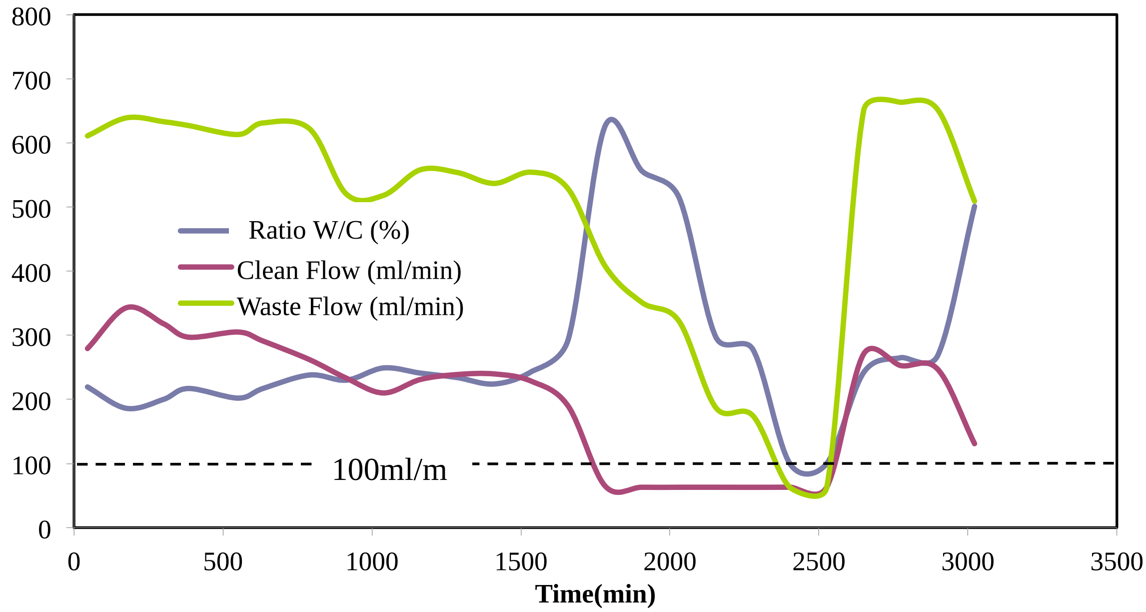

Figure 45. Tata Swach Platina RO Filter Flow Performance

Percent Recovery

The two RO filters (Clean Water Dolphin and Tata Swach Platina) that CITE tested in the Consumer Reports lab had an average percent recovery rate of 28% and a range from 25% to 32%, or a ratio of about 1:4 or 1:3 of clean water to wastewater. (The data for this result is shown in Appendix C.)

Overall, RO filters were shown to be quite effective in removing high levels of *E. coli* bacteria (10^5 to 10^6 Most Probable Number (MPN)/100 mL), in reducing the high turbidity (40 NTU), and in removing substantial TDS (1500 mg/L) in the challenge water. The RO Dolphin (Clean Water model) filter was seen to be comparable in its performance to the branded Tata Swach Platina RO model, which costs three times more. One test on both the Clean Water Dolphin RO and the Tata Swach Platina RO showed that the Tata Swach Platina had a significantly shorter life compared with the Clean Water Dolphin model. The Tata Swach showed a lifetime of 29 hr. (1430 L), whereas the Clean Water Dolphin registered a lifetime of 46 hr. The average percent recovery was 26% for the Clean Water Dolphin and 30% for the Tata Swach Platina.

Comparative Ratings Chart and Discussion

In this section, the performance testing for the GNE and RO filters is presented in a Consumer Reports-style comparative ratings chart (see Table 23). Ratings for cloth and mesh filters were not included in the comparative ratings chart because the quality of the products was so poor that doing so would have skewed the results of the other product categories. In addition, the turbidity and *E. coli* removal data for this category of filters were limited. Instead, cloth and mesh filters are summarized broadly in text and table form, comparing cloth and mesh as one category (conventional particle filters) with the GNE and RO categories.

Cloth and Mesh Filters

As a low-cost method used in Indian households, the cloth and mesh filters were found to have a limited ability to provide clean, safe drinking water. Colwell et al. (2003) found in Bangladesh that local sari cloth folded at least four times can effectively remove higher than 99% of *V. cholera* attached to plankton. According to their research, the local sari folded 4 to 8 times has a pore size of about 20 μm, so it can remove most of the *V. cholera* attached to plankton that are mostly bigger than 20 μm. In this research, the *E. coli* used is about 0.25 to 1.0 μm in diameter and 2.0 μm in length, the cloth tested has a pore size of 30 to 300 μm, and the mesh size is about 300 μm. Thus, the cloth and mesh filters have very limited ability to reduce *E. coli* bacteria at a maximum of about 20%. Turbidity reduction is possible, but is also very limited at a maximum of about 60%. The fine dust used has a particle size from 1 to 100 μm (Appendix A), so the turbidity reduction of the cloth filters is limited even with 4 to 8 layers. Nonetheless, the India team found that conventional cloth and mesh particle filters are used throughout households in Ahmedabad. While the CITE team noted the need for substantial design improvements, this category of filters shows great opportunity for innovation that could reach millions of users, especially poor families in India.

Table 19. Performance Summary for Each Filter Category

Filter Category	*E. coli* Removal	Turbidity Removal	TDS Removal	Flow Rate
Cloth & Mesh	Poor	Poor	Poor	Excellent
GNE Filters	Fair to Good	Fair to Good	Poor	Poor to Fair
RO Filters	Excellent	Excellent	Excellent	Excellent

Additionally, Table 20 below compares the filter categories for their cost (purchase and operating), lifetime, and impact on the environment based on percent recovery results of RO units.

Table 20. Comparison among Filter Categories of Cost, Lifetime, and Environmental Factors

Filter Category	**Purchase Cost (US $)**	**Operating Cost (US $)**	**Life of Filter Elements**	**Environmental Factors**
Cloth & Mesh	Very low	Very low	Long with washing	None
GNE Filters	Moderate	Moderate	Short to long	None
RO Filters	High to very high	High[16]	Long	Significant wastewater

OVERVIEW OF COMPARATIVE RATINGS CHART

Consumer Reports-style comparative ratings charts for the RO filters and GNE filters are provided to highlight the results of this research. Consistent with Consumer Reports, CITE used "icons" in the presentation of the S1-Consumer Reports lab research. This is also consistent with the suitability research conducted in India and with CITE's scalability and sustainability research. The icons are shown below in black and white.

KEY: ● Excellent; ◕ Very Good; ◑ Good; ◔ Fair; ○ Poor.

The comparative ratings chart is a decision support tool for agencies and consumers when deciding on the purchase and use of water filters. These ratings charts were developed following a Consumer Reports-style of evaluation: they differentiate among various filter models found on the marketplace in Ahmedabad based on their key attributes and features. Each attribute was tested in a customized laboratory designed through the collaboration between Massachusetts Institute of Technology researchers and Dr. Jeffrey Asher, V.P. and Technical Director, retired, of Consumer Reports. The definition of each attribute has already been described.

In order to develop this chart, several key concepts—scores, weightings, and ratings—need to be introduced. To grasp these key concepts, the reader should refer to Table 23, which shows the S1-Consumer Reports comparative ratings chart for RO and GNE water filters.

[16] RO operating cost can be very high if the cost of water is taken into account.

Scores, Weightings, and Ratings

This section defines the key concepts and explains how attribute scores and weightings are determined in creating a comparative ratings chart. Further details regarding scoring, weighting, and the comparative ratings method are described in Appendix D.

"**Score**" is a numerical "grade" given to each attribute (clean flow rate, turbidity reduction, etc.) or feature of each model. The performance of each model for each test attribute determines the raw score. This score is placed on a scale ranging from 0.50 to 5.49 based on a linear best fit tied to the standard deviation of the set scores (see Appendix D). The scores are then translated into graphical icons found in the comparative ratings chart (Table 23).

"**Weighting**" is the level of significance given to each attribute in order to compute a composite or overall rating for the attributes. The CITE team determined weightings based on how important an attribute was to the safety of the water, but these weightings could be adjusted by the chart user in order to select which attributes are most important to that particular user. For example, *E. coli* removal could be weighed more heavily than turbidity removal, which is more of an aesthetic water characteristic. The attribute weightings for the GNE filters are shown in Table 22. For *E. coli* removal, since fecal contamination should never or very rarely appear, in the feed water, it is weighted at only 10% in our example. In areas where there is considerable *E. coli* contamination in the inlet water, this weighting would be increased since the attribute's priority would be high. The clean water flow rate is weighted at 50%, which is to say, it is weighted as a very important factor. If there is not a satisfactory flow, the consumer will not use the filter.

Table 22. Weightings for Each Attribute of GNE Filters

Attribute	*E. coli* LRV	Turbidity Removal	TDS Removal	Flow Rate	TDS Removal	Lifetime
Weighting (%)	10	20	0	50	0	20

"**Rating**" is the overall weighted sum of the attributes and feature scores for each model to produce an "overall score." It is scaled in a range between 0 and 100.

"**Overall Score**" is the overall assessment for each model in a concise way to help agencies and consumers make better-informed purchasing decisions.

Attributes and Features Shown in the Ratings Charts

Different purchasers would have different priorities for filter performance. The attributes and features that are shown in the ratings charts are interpreted below. Agencies or consumers can change these weightings to fit their own priorities.

E. coli Removal

Metric: Log removal value (LRV) of *E. coli* colonies
Scoring: Higher log removal value is favorable

This test assesses the ability of the water filters to remove the high levels of *E. coli* bacteria in the inlet. The *E. coli* levels are measured in the inflow and outflow clean water for all filter categories, as well as in the wastewater for RO filters. The scoring is for the clean water % removal effectiveness, which is expressed as an LRV. This LRV measurement is done at the beginning, middle-of-life, and end-of-life for each filter sample.

Turbidity Removal

Metric: Level of turbidity % removal
Scoring: Higher % removal of turbidity in clean water is favorable

Turbidity (created using A2 dust) was added to the water in the 100-gallon water tanks and monitored to keep it at approximately 40 NTU. Measurements were done periodically throughout the lifetime of the filter to determine the reduction of turbidity in the clean water for each model, as well as its increase in the wastewater for the RO filter. The score is based on the turbidity % removal in the clean water.

Total Dissolved Solids (TDS) Removal

Metric: Level of TDS % removal
Scoring: Higher % removal in TDS in clean water is favorable

TDS (made from Epsom salts) was added to the water in the 100-gallon water tanks and monitored to keep it at approximately 1500 mg/L. Measurements were done periodically throughout the lifetime of the filter to determine the reduction of TDS in the clean water for each model as well as its increase in the wastewater for the RO filter. The score is based on clean water TDS removal.

Clean (“Product”) Water Flow Rate

Metric: Clean water flow rate
Scoring: Higher flow rate is favorable

The clean water flow rates were measured throughout the lifetime of each filter sample. The scoring for the clean water flow rate was different for each filter category—particle removal, GNE, and reverse osmosis (RO) models—because of their large range of flow rates.

RO Percent Recovery

Metric: Percent recovery
Scoring: Higher percent recovery is favorable

The two RO filters CITE tested in the Consumer Reports lab had an average percent recovery rate of 28% and a range from 25% to 32%, or a ratio of about 1:4 or 1:3 of clean water to wastewater. A high wastewater flow rate means that water—a precious resource—is being wasted. Thus, a higher percent recovery is more environmentally friendly, and it can save the user money if there is a fee for each gallon used and treated with a household RO filter.

Filter Lifetime/Clogging

Metric: Number of hours the filter operates before its clean water flow rate is below 1 L/hr. for GNE filters, and below 100 mL/min. for RO filters
Scoring: Longer filter lifetime is favorable

The clean water flow rate diminishes with time as the filter is used. Clogging measures how well the filter retains its flow rate of clean water over time and how often the users need to change the filter or cartridge. A longer lifetime means less filter maintenance and less replacement cost.

S1-Consumer Reports Comparative Ratings Chart

Table 23 is the synthesis of all the S1-Consumer Reports' results in the form of a Consumer Reports-style comparative ratings chart. The chart shows the top performers in each category. In addition, it shows the "value for money," or the relative performance increase as a function of price. This allows those making decisions to balance the tradeoffs between overall performance and price, as well as among the various attributes when making a purchasing decision. The user of the chart may choose to select a model by the highest overall score, by the score as a function of price, or by critical factors relating to their specific situation.

Reverse Osmosis (RO)

Two reverse osmosis filters were tested for their product lifetime over a period of about three weeks using the RO flow test rig. Generally, RO filters are quite effective in cleaning "challenge water" that has very high levels of *E. coli* bacteria (10^5 to 10^6 MPN/100 mL), turbidity (40 NTU), and TDS (1500 mg/L). Based on these lifespan tests, the RO dolphin-type filter (Clean Water model) was as effective as the branded RO filter (Tata Swach Platina model) that was three times more expensive. These results are very good news for the consumer. However, RO filters in general represent a poor tradeoff for the environment, because they generate a large amount of wastewater during operation.

In the marketplace in India, a number of Dolphin-type RO models are available for households. From a close look at the inside structure of the three models from different manufacturers, they all have the same basic design, which is similar to the high-priced branded RO filters. But, it was evident that some features such as backwash were eliminated in the Dolphin-type filters and cheaper materials were used inside. This suggested to the S1-Consumer Reports research team that while the Dolphin filter performed well initially, this performance might not be sustainable. Nonetheless, in terms of the performance of the Clean Water (US $98) that was extensively tested, Dolphins did as well as, if not better than, the Tata Swach Platina (US $300). Future research should be done with more test samples and more filter models in both price ranges to confirm these findings.

Gravity Non-Electric (GNE) Filter

It can be seen from the GNE section of the Table 23 comparative ratings chart that none of these GNE filters have an excellent performance for all attributes. Rather, a GNE model is seen as good in one performance aspect, but falls down in another. Take the Cristella Plus filter made by Tata Swach as an example: it is a good buy at US $17, with the second-highest flow rate of 3.96 L/hr. and the longest life, but poor in *E. coli* removal. This would be the best choice for water sources without microbial contamination, such as a reliable piped water supply for a reliable municipal source. However, if bacteria is a concern in the water sources, then the PureIt by Hindustan Unilever at US $17 may be the answer, because it has good *E. coli* removal and the best flow rate compared to other models that had good *E. coli* removal.

Table 23. S1-Consumer Reports' Comparative Ratings Chart

Product Information					Product Attributes									Product Features		
Category	Model	Overall Score	Cost in Dollars [1]		*E.Coli* Removal	Turbidity Reduction	TDS Reduction [3]	Clean Water Flow		Percent Recovery [6]		Lifetime	Convenience	Pre-filter	Auto or natural shut off	Power or life Indicator
		0 to 100	Purchase	Operating [2]				Liters/Hr	Score	%	Score					
Reverse Osmosis	Clean Water Dolphin	90	$98	$369	Excellent	Excellent	Excellent	14.5	Excellent	27	Good	Excellent	Very Good	Yes		
	Tata Swach Platina	88	$233	$668	Excellent	Excellent	Excellent	14.0	Excellent	31	Very Good	Very Good	Excellent			
Gravity Non Electric	Eureka Forbes AquaSure Amrit	56	$42	$489	Good	Excellent	-	4.00	Excellent	-	-	Fair	Excellent	Yes	Yes	Yes
	Tata Swach Smart 1500 liters	53	$20	$252	Fair	Excellent	-	3.27	Good	-	-	Very Good	Excellent	Yes	Yes	Yes
	Hindustan Lever PureIt Class 14L	52	$17	$537	Very Good	Excellent	-	3.40	Good	-	-	Poor	Good	Yes	Yes	Yes
	Tata Swach Smart w. Silver NANO 3000 liters	51	$17	$537	Fair	Excellent	-	2.21	Good	-	-	Good	Excellent			
	Prestige LifeStraw	51	$50	$135	Very Good	Excellent	-	1.61	Poor	-	-	Fair	Very Good	Yes		
	Kent Gold UF Membrane Filter	50	$43	$183	Very Good	Excellent	-	3.10	Good	-	-	Poor	Poor	Yes	Yes	Yes
	Tata Swach Cristella Plus	47	$17	$537	Poor	Good	-	3.96	Excellent	-	-	Excellent	Excellent	Yes	Yes	
	Expresso Stainless Steel Water Container [4]	43	-	-	Very Good	Excellent	-	0.61	Poor	-	-	Excellent	Fair			
	Everpure Unbreakable [5]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Conventional Particle	Ratings for cloth and mesh filters were not generated because the lowest category "poor" did no capture the inadequacy of their performance and would skew the other ratings.															

Legend

- Excellent
- Very Good
- Good
- Fair
- Poor

Attribute Definitions

E.coli removal	percentage of E.coli removed by the filter
Turbidity reduction	percentage of turbidity removed by the filter
Total dissolved solids reduction	percentage of total dissolved solids removed by the filters
Clean water flow	liters of clean water a filter produced per hour
Percent recovery	percentage of clean water produced out of total water poured into filter
Lifetime	a measure of how well the filters retains its flow rate of clean water over time
Convenience	a measure balancing value added by features that facilitate water filtering & value detracted by features that hinder water filtering

Notes

Overall Score ranges from 0 to 100, with 0 as low and 100 as high.

[1] – The exchange rate used for this calculation is 60 INR per USD.

[2] – Operating cost is the total cost of ownership (TCO), which averages the initial purchase price plus the cost of the replacement parts for a household consuming 25 liters per day over the five-year lifetime of the device.

[3] – Gravity non-electric filters as a product category are not designed to remove total dis solved solids.

[4] – Multiple samples never met the minimum flow rate of 1 liters per minute

[5] —There were significant leaks found in multiple samples of the Everpure Unbreakable, making the quality impossible to test.

[6] —Percent recovery only applies to reverse osmosis filters which produce wastewater.

Discussion of the Comparative Ratings Chart

This suitability comparative ratings chart was developed to enhance the ability of agencies and consumers to make informed purchasing choices. The comparative ratings chart includes all the necessary technical information required to make these decisions. Non-technical factors were not assessed in this thesis, such as the supply-chain, retail and distribution markets, cultural acceptability of water filters, and the maintenance, warranty, and accessibility/customer support offered by the manufacturers. However, they were assessed by CITE's sustainability and scalability research teams.

Conclusions

Fifteen models were tested in the Consumer Reports lab under "ideal" conditions on the basis of three filter categories. This included four CPF, nine GNE, and two RO models.

Conventional Particle Filters – Cloth and Mesh

- Cloth filters had limited effectiveness in reducing turbidity. Folding the best cloth model four times reduced turbidity only by about 60%.
- Cloth filters had little impact on removing *E. coli* (less than 20%) and no impact on removing total dissolved solids (TDS) (0%), no matter how many layers were folded.
- *Jali* mesh type filters likewise had limited effectiveness in reducing turbidity (5%) and none in removing *E. coli* (0%).
- Thus, the cloth and mesh filters need to be redesigned in India with smaller mesh size and higher performance. An improved CPF or GNE filter that is clearly proven to effectively remove *E. coli* and turbidity—and that is very low cost with high user demand—is an opportunity for innovation.

Gravity Non-Electric Filters

None of the GNE filters have superlative performance. Some are good in one performance aspect, but poor in another. An illustrative example is the Cristella Plus GNE filter made by Tata (a good buy at US $29), which had one of the highest flow rates and the longest life, but was poor in *E. coli* removal.

- There are big differences among the GNE filters regarding their effectiveness in terms of flow rate, turbidity removal, lifetime, and *E. coli* removal. In general, the higher the flow rate, the lower the turbidity removal, as well as the lower the *E. coli* removal.
- Three models can remove higher than 99.99% *E. coli*, while the others can remove greater than 99%.
- Five models—Expresso, Hindustan Unilever's PureIt, Prestige's LifeStraw, AquaSure's Amrit with Kitanu Magnet, and KENT's Gold UF Membrane Filter—were able to remove higher than 95% turbidity during their lifetime.
- The Expresso unit was very slow in producing clean water. The manufacturer indicated that "during the first 15 days of any new candle, the flow is slow." We found that even after 15 days, the Expresso's flow did not increase. Further, the clean water flow rate of the Expresso remained below 1 L/hr., our cutoff for filter end-of-

life for GNE models. Thus, this filter model was seen to have a lifetime of zero, failing to produce a sufficient flow of water.

Reverse Osmosis

- Reverse osmosis filters were shown to be quite effective in reducing high levels of contaminants from the "challenge water," which included *E. coli* bacteria (10^5 to 10^6 MPN/100 ml), turbidity (40 NTU), and TDS (1500 mg/L).

- Based on lifetime tests of reverse osmosis models, the locally assembled RO Dolphin filter (Clean Water model) was as effective as a branded RO (Tata Swach Platina model). The RO Dolphin filters appear to be knockoffs of major brands, but were seen to be as effective as their RO branded counterparts, which were two to three times more expensive.

- RO systems generate significant amounts of wastewater. Independent of whether it is a non-branded Dolphin or a branded system, RO systems generate "permeate" (clean water) and "concentrate" or "brine," also known as "wastewater." The Clean Water Dolphin and the Tata Swach Platina RO, which were the two household RO systems that S1-Consumer Reports tested for its clean water versus wastewater output, had percent recovery rates of 25% to 32%. That means a ratio of clean water to wastewater of about 1:4 or 1:3. From an environmental sustainability perspective, this is of particular concern in water-scarce regions and of general concern on a water-limited planet. While RO systems may be appropriate in improving the aesthetics and acceptability of drinking water in areas where groundwater is high in total dissolved solids, hardness, or salinity, in its waste of water, RO household water systems are not a recommended option for Gujarat and other dry regions of India. ROs should be targeted mainly for areas with an overabundance of water.

- For the two Dolphin filter models from India, surprisingly, both came with a 24 VDC[17] motor, 36 VDC solenoids, and a 36 VDC power supply. Neither of the two Dolphins was refined in its construction, unlike the branded RO models. Nonetheless, the Clean Water Dolphin model performed as well as the branded ROs, including the Swach Platina RO by Tata. Only one sample of each RO model was lifetime tested,[18]

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[17] VDC is an acronym for "Volts Direct Current." VDC is often shown on electrical schematics to indicate a connection to the positive side of a battery or other DC power source.

[18] Filter lifetime measures how long a filter can retain its clean water flow rate. For RO filters evaluated in this study, filter lifetime was defined as when clean water flow rate fell below 100 mL/min. For GNE filters, our study defined

so these results are preliminary.

- Test methods and two special test rigs were developed that made these water filter product evaluations more cost-effective. These test rig modifications and inventions included: (a) a system to inject the pathogens directly into the filter inlet, and (b) an automated rig to test multiple RO filters at the same time.

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filter lifetime as when a clean water flow rate fell below 1 L/hr. This is a factor related to the convenience of using the filter and the lifetime cost of the filter.

APPENDICES

APPENDIX A. ISO 12103-1/CD, A2 Fine Test Dust Specification

PTI Powder Technology Inc.
14331 Ewing Ave S
Burnsville, MN 55306
Ph: 952-894-8737

ISO 12103-1/CD, A2 FINE T.D.

PTI ID: 12164F

OPERATOR: LHA

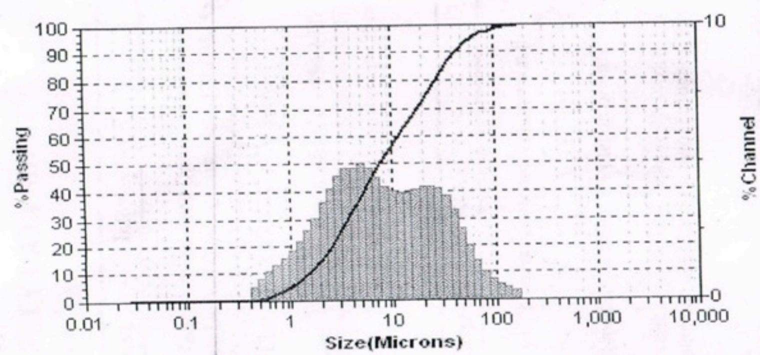
05/05/2014
09:37

Microtrac S3500

ISO 12103-1/CD, A2 FINE TEST DUST
H2O CARRIER, 30 SEC. ULT-SON

D

PTI Powder Technology Inc.
14331 Ewing Avenue South Burnsville, Minnesota 55306
Phone: 952-894-8737



Size(um)	%Tile
0.970	5.17
1.380	9.19
2.750	22.43
5.50	41.75
11.00	59.24
22.00	75.36
44.00	90.81
88.00	97.90
124.5	99.21
176.0	100.00

Distribution:	Volume	Run Time:	30 Sec	Fluid:	CURRENT CARRIER		
Progression:	Geom 4 Root	Run#:	Avg of 3	Fluid Ref Index:	1.333	Loading Factor:	0.0599
Up Edge(um):	1408	Particle:	DEFAULT PARTICLE	Above Residual:	0	Transmission:	0.876
Low Edge(um):	0.0215	Transparency:	Transparent	Below Residual:	0	RMS Residual:	0.502%
Residuals:	Disabled	Part. Ref. Index:	1.51			Flow:	50 %
#Channels:	64	Particle Shape:	Irregular	Cell ID:	1720	Usonic Power:	N/A
Analysis Mode:	S3000/3500			Multi Run Delay:	0 Min.	Usonic Time:	N/A
Filter:	Enabled	DB Record:	1179	Recalc Status:	Original	Serial Number:	S4840
Analysis Gain:	Default(2)	Database:	Z:\S3500\Databases\ISO FINE TD.MDB				

Data	Value
MV(um):	16.58
MN(um):	0.806
MA(um):	3.71
CS:	1.617
SD:	14.75
Mz:	13.70
σι:	16.26
Ski:	0.707
Kg:	1.289

%Tile	Size(um)
10.00	1.462
20.00	2.489
30.00	3.64
40.00	5.18
50.00	7.45
60.00	11.38
70.00	17.59
80.00	26.66
90.00	42.04
95.00	59.58

Size(um)	%Chan	% Pass	Size(um)	%Chan	% Pass
1408	0.00	100.00	3.89	4.88	31.87
1184	0.00	100.00	3.27	4.56	26.99
995.6	0.00	100.00	2.750	4.11	22.43
837.2	0.00	100.00	2.312	3.58	18.32
704.0	0.00	100.00	1.945	3.04	14.74
592.0	0.00	100.00	1.635	2.56	11.70
497.8	0.00	100.00	1.375	2.15	9.14
418.6	0.00	100.00	1.156	1.80	6.99
352.0	0.00	100.00	0.972	1.52	5.19
296.0	0.00	100.00	0.818	1.29	3.67
248.9	0.00	100.00	0.688	1.06	2.38
209.3	0.00	100.00	0.578	0.80	1.32
176.0	0.35	100.00	0.486	0.52	0.52
148.0	0.44	99.65	0.409	0.00	0.00
124.5	0.56	99.21	0.344	0.00	0.00
104.7	0.75	98.65	0.2890	0.00	0.00
88.00	1.03	97.90	0.2430	0.00	0.00
74.00	1.43	96.87	0.2040	0.00	0.00
62.23	1.98	95.44	0.1720	0.00	0.00
52.33	2.65	93.46	0.1450	0.00	0.00
44.00	3.31	90.81	0.1220	0.00	0.00
37.00	3.83	87.50	0.1020	0.00	0.00
31.11	4.12	83.67	0.0860	0.00	0.00
26.16	4.19	79.55	0.0720	0.00	0.00
22.00	4.16	75.36	0.0610	0.00	0.00
18.50	4.07	71.20	0.0510	0.00	0.00
15.56	3.97	67.13	0.0430	0.00	0.00
13.08	3.92	63.16	0.0360	0.00	0.00
11.00	3.98	59.24	0.0300	0.00	0.00
9.25	4.18	55.26	0.02550	0.00	0.00
7.78	4.50	51.08			
6.54	4.83	46.58			
5.50	5.02	41.75			
4.62	4.86	36.73			

APPENDIX B. PARTS LIST

The table below provides listings of the critical parts required for the water filter product testing setup and for potentially scaling up the number of RO filters that can be simultaneously evaluated in the future.

Plumbing and Electrical Parts List

	Item	Quantity	Manufacturer	Model Number	Unit US $	Total US $
1	100-Gallon (378 L) Tank	3	Ace/DenHartog	NSF-61	$152.99	$458.97
2	Stainless Steel Circulator 1/8HP	3	Taco	0014-SF1	$404.95	$1,214.85
3	1" Stainless Steel Freedom Flange (pair)	3	Taco	110-252SF	$27.35	$82.05
4	Thermoplastic Shallow Well Jet Pump 3/4 HP	1	Flotec	FP4022-10	$335.82	$335.82
5	Pre-charged Water Tank	1	Dayton	3GVU1	$560.00	$560.00
6	Pressure Switch	1	Furnas	69WEC	$88.95	$88.95

Electronics Parts List to scale up simultaneously

	Item	Quantity	Manufacturer	Model Number	Unit US $	Total US $
1	Solenoid Valve	8	DEMAG	DEMA 41-9-5	$23.13	$185.04
2	NI Compact DAQ 4-Slot USB Chassis	1	National Instruments (NI)	NI cDAQ-9174	$777.00	$777.00
3	8 Channel Solid State Relay Module	1	National Instruments	NI 9485	$616.00	$616.00
4	8 Channel, 500 kS/s Voltage Module	1	National Instruments	NI 9201	$3,708.00	$3,708.00

NOTES:

1) Requires a paid LabView license.

2) One flow meter and one pressure transducer have already been purchased by MIT.

3) For each National Instruments (NI) "8-channel" system, four flows can be measured. Two RO filters require 8 channels for testing filters simultaneously.

4) We also need a Windows laptop to install the LabView and NI software. The Consumer Reports version of this software will be provided to MIT, but MIT staff will need to become conversant with it for future software changes.

5) This parts list does not include miscellaneous metal and PVC pipes/valves/fittings.

APPENDIX C. RO FLOW TESTING SAMPLE DATA

RO Flow Testing – Measurement Sequencing

RO Flow Run 13 _ Models 32 and 23 – 2_120_240_124_0818									
	SOLENOID KEY: "0" Closed and "1" Opened								
Cycle	Solenoid 1	Solenoid 2	Solenoid 3	Solenoid 4	Solenoid 5	Solenoid 6	Solenoid 7	Solenoid 8	Time (Sec.)
ALL: No measurement – Cycle #1	0	1	0	1	0	1	0	1	240
RO #1: Clean	1	0	0	1	0	1	0	1	120
RO #1: Waste	0	1	1	0	0	1	0	1	120
RO #2: Clean	0	1	0	1	1	0	0	1	120
RO #2: Waste	0	1	0	1	0	1	1	0	120
ALL: No measurement – Cycle #2	0	1	0	1	0	1	0	1	240
RO #1: Clean	1	0	0	1	0	1	0	1	120
RO #1: Waste	0	1	1	0	0	1	0	1	120
RO #2: Clean	0	1	0	1	1	0	0	1	120
RO #2: Waste	0	1	0	1	0	1	1	0	120
ALL: No measurement –	0	1	0	1	0	1	0	1	240

Cycle #3									
RO #1: Clean	1	0	0	1	0	1	0	1	120
RO #1: Waste	0	1	1	0	0	1	0	1	120
RO #2: Clean	0	1	0	1	1	0	0	1	120
RO #2: Waste	0	1	0	1	0	1	1	0	120
|									
ALL: No measurement – Cycle #9	0	1	0	1	0	1	0	1	240
RO #1: Clean	1	0	0	1	0	1	0	1	120
RO #1: Waste	0	1	1	0	0	1	0	1	120
RO #2: Clean	0	1	0	1	1	0	0	1	120
RO #2: Waste	0	1	0	1	0	1	1	0	120
ALL: No measurement – Cycle #10	0	1	0	1	0	1	0	1	240
RO #1: Clean	1	0	0	1	0	1	0	1	120
RO #1: Waste	0	1	1	0	0	1	0	1	120
RO #2: Clean	0	1	0	1	1	0	0	1	120
RO #2: Waste	0	1	0	1	0	1	1	0	120
ALL: No measurement – END	0	1	0	1	0	1	0	1	240
Total (min.) =									124

RO Flow Testing – Flow Measurements

RO Flow Run 13 _ Models 32 and 23 – 2_120_240_124_0818													
						Measured RO #1-Clean							
Row#	Date	Time	Pressure PSI	Flow mL/min	Total mL	Solenoid 1	Solenoid 2	Solenoid 3	Solenoid 4	Solenoid 5	Solenoid 6	Solenoid 7	Solenoid 8
1	14-8-18	8:23:37 AM	0.8217	1.4980	0.0279	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
2	14-8-18	8:23:39 AM	0.7673	1.4758	0.0759	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
3	14-8-18	8:23:41 AM	0.7818	1.5106	0.1254	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
4	14-8-18	8:23:43 AM	0.7552	1.4253	0.1737	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
5	14-8-18	8:23:45 AM	0.8439	1.4960	0.2227	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
6	14-8-18	8:23:47 AM	0.8540	1.4798	0.2712	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
7	14-8-18	8:23:49 AM	0.8359	1.5141	0.3203	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
8	14-8-18	8:23:51 AM	0.7711	1.5057	0.3681	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
9	14-8-18	8:23:53 AM	0.8001	1.4956	0.4177	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE

	| ETC |												
47	14-8-18	8:25:10 AM	0.7324	1.4715	2.2988	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
48	14-8-18	8:25:12 AM	0.7289	1.4879	2.3482	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
49	14-8-18	8:25:14 AM	0.7108	1.5182	2.3988	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
50	14-8-18	8:25:16 AM	0.7039	1.5690	2.4472	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
51	14-8-18	8:25:18 AM	0.7197	1.4819	2.4975	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
52	14-8-18	8:25:20 AM	0.6788	1.5044	2.5488	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
53	14-8-18	8:25:22 AM	0.5776	1.5807	2.6007	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
54	14-8-18	8:25:25 AM	0.6341	1.5303	2.6538	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
55	14-8-18	8:25:27 AM	0.5430	1.5085	2.7053	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
56	14-8-18	8:25:29 AM	0.5493	1.5384	2.7556	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
57	14-8-18	8:25:31 AM	0.5744	1.5334	2.8068	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
58	14-8-18	8:25:33 AM	0.5356	1.5690	2.8586	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE

59	14-8-18	8:25:35 AM	0.6260	1.5424	2.9102	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE
							Measured RO #1- Waste						
	Date	Time	Pressure PSI	Flow mL/min	Total mL	Solenoid 1	Solenoid 2	Solenoid 3	Solenoid 4	Solenoid 5	Soleno id 6	Solenoid 7	Solenoid 8
61	14-8-18	8:25:37 AM	0.7370	4.1479	0.1074	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE
62	14-8-18	8:25:39 AM	0.8520	4.6081	0.2572	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE
63	14-8-18	8:25:41 AM	0.7962	4.5511	0.4099	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE
64	14-8-18	8:25:43 AM	0.8096	4.4870	0.5570	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE
65	14-8-18	8:25:45 AM	0.7692	4.4471	0.7060	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE
66	14-8-18	8:25:47 AM	0.7989	4.4827	0.8541	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE
	| ETC												

RO Flow Testing – Data Analysis

		Clean Water Dolphin				Tata Swach Platina RO						
Measur e-ment	Ratio W/C	Clean RO	Waste RO	% Recover	Ratio W/C	Clean RO#2	Waste RO#2	% Recover	Slope > >	0.0102	0.4369	<< Intercept>

80

#	#1 (%)	Flow #1	Flow #1	y	#2 (%)	Flow	Flow	y				>
		(mL/min)	(mL/min)	(%)		(mL/min)	(mL/min)	(%)	<<<FLOW MEASUREMENT (volts) >>>			
									Clean RO #1 Flow	Waste RO #1 Flow	Clean RO #2 Flow	Waste RO #2 Flow
1	260%	189	492	28%	275 %	155	428	27%	1.4938	4.5844	1.1482	3.9239
2	300%	207	622	25%	213 %	261	558	32%	1.6786	5.9072	2.2294	5.2531
3	316%	206	651	24%	235 %	240	564	30%	1.6647	6.2076	2.0138	5.319
4	277%	244	674	27%	228 %	255	583	30%	2.049	6.4366	2.1687	5.5111
5	282%	236	664	26%	229 %	246	563	30%	1.9662	6.341	2.0736	5.302
6	284%	230	654	26%	234 %	237	554	30%	1.9089	6.2324	1.9781	5.2135
7	310%	220	683	24%	241 %	238	574	29%	1.808	6.531	1.9926	5.419
8	285%	240	685	26%	219 %	264	578	31%	2.0138	6.5473	2.2534	5.4594

9	282%	242	683	26%	225 %	256	576	31%	2.0338	6.5326	2.1767	5.4413
10	281%	239	672	26%	239 %	234	560	29%	2.001	6.4127	1.948	5.271
Average	288%	225	648	26%	234 %	239	554	30%	1.8618	6.1733	1.9983	5.2113

APPENDIX D. FURTHER DETAILS ON SCORING, WEIGHTING, AND RATING METHODS FOR THREE FILTER CATEGORIES

A comparative ratings chart provides consumers and institutions with the information and guidance for deciding which filter can serve their needs best at the lowest price. Developing a ratings chart involves three key aspects:

Scoring: In general, a linear relationship is assumed between a filter's performance on a certain attribute and the filter's rating score assigned for this attribute when converting attribute performance to a rating score. For example, a filter's attribute, such as its turbidity removal ability, should be linearly converted to a rating score ranging from 0.50 (poor) to 5.49 (excellent).

Weighting: After giving each filter a rating score for each of the attributes, each attribute is weighted according to its importance, to compute the overall score for the GNE filters and the reverse osmosis filters.

Ratings: Ratings is the overall score of each individual filter model, scaled in a range between 0 and 100. The rating of each filter model indicates the filter's overall performance.

Turbidity removal converting: We take the turbidity removal at each filter's middle-of-life as the indicator of the filter's general turbidity reduction performance. As shown in Appendix Table D.1.2, there are two fixed turbidity removal limits—at 100% the score should be 5.49 (excellent), and at 0% the score is 0.5 (poor). By inserting a 50% removal rate for a score of 3 and a 10% removal for a score of 1, we can compute the linear relationship between turbidity removal (TR) and the score (S). The linear fitting by computer shows the function is:

$S=5\times TR+0.5$

Taking the water filter of the Expresso stainless steel water container as an example, the turbidity removal at its middle-of-life is 98.20% as shown in Appendix Table D.1.1. Thus, its attribute score for turbidity removal is $5\times0.982+0.5=5.41$.

Flow rate converting: Each filter's flow rate at its middle-of-life was also used for representing the filter's ability to produce clean water. In Appendix Table D.1.2, 5.00 L/hr. is inserted for a score of 3 and 1.00 L/hr. for a score of 1. Thus, the linear relationship between the middle-of-life flow rate (FR) and the score (S) is:

$S=0.5\times FR+0.5$

Using the Expresso again as an example, the flow rate at its middle-of-life is 0.61 L/hr. as shown in Appendix Table D.1.1. Thus, its attribute score for flow rate is $0.5\times0.61+0.5=0.81$.

Appendix D, Table 1 – Attribute Scores for Each Filter Model

Model	Turbidity Removal		Flow Rate		Lifetime		*E.coli* LRV	
	Value (%)	Score	Value(L/hr)	Score	Value (day)	Score	Value	Score
Stainless Steel Water Container (Expresso)	98.20%	5.41	0.61	0.81	NA	0.50	>4	4.00
Christella Plus (TATA Swach)	76.24%	3.00	3.96	2.48	44.32	5.00	1.72	1.72
Pureit Classic 14L (Hindustan Unilever)	98.69%	5.43	3.40	2.20	2.38	1.06	>4	4.00
LifeStraw (Prestige)	98.43%	5.42	1.61	1.31	5.22	1.50	>4	4.00
AQUASURE AMRIT WITH KITANU MAGNET (EUREKA FORBES)	98.87%	5.44	4.00	2.50	5.88	1.60	3.20	3.20
KENT Gold UF Membrane Filter	98.28%	5.41	3.10	2.05	2.59	1.09	>4	4.00
Swach Smart (TATA) 1500 liters	91.38%	4.50	3.27	2.14	24.31	4.43	2.24	2.24
Swach Smart (TATA) with Silver NANO 3000 liters	97.76%	5.39	2.21	1.61	12.82	2.66	2.60	2.60

Note: The numbers marked gray are manually supplied.

Appendix D, Table 2 – Converting between Attribute Performance and Attribute Score

SCORING	Turbidity Removal		Flow Rate		Lifetime		*E.coli* LRV	
	Value	Type	Value(L/hr)	Type	Value (day)	Type	Value	Type
5.49 =	1.00	Computed	9.98	Computed	31.19	Computed	5.49	Computed
5.00 =	0.90	Computed	9.00	Computed	28.00	Computed	5.00	Computed
4.00 =	0.70	Computed	7.00	Computed	21.50	Computed	4.00	Computed
3.00 =	**0.50**	**Fixed**	**5.00**	**Fixed**	**15.00**	**Fixed**	3.00	**Fixed**
2.00 =	0.30	Computed	3.00	Computed	8.50	Computed	2.00	Computed
1.00 =	**0.10**	**Fixed**	**1.00**	**Fixed**	**2.00**	**Fixed**	1.00	**Fixed**
0.50 =	0.00	Computed	0.00	Computed	-1.25	Computed	0.50	Computed

Lifetime converting: This attribute transformation follows the same pattern as the previous one for flow rate. The linear function for lifetime (LT) and score (S) is:

$S=0.1538\times FR+0.6923$

Appendix Table D.1.1 shows that the lifetime of the Cristella Plus (Tata Swach) is 44.32 days, so the attribute score for lifetime is $0.1538\times 44.32+0.6923=7.51$.

TDS removal converting: There is none, because the TDS reduction was zero for all GNE models.

***E.coli* LRV converting**: The average of *E.coli* LRV at each filter's beginning-of-life and end-of-life was computed to represent the filter's overall *E.coli* removal performance. Then the averaged *E.coli* LRV was converted to an attribute score according to Appendix Table D.1.2.

Convenience converting: The convenience score consists of two parts—convenience factors and features. Each is shown compiled in Appendix Table D.1.3 along with the scoring used for the GNE filters. In this case, the convenience factors are actually "inconvenience" attributes, and the score is a negative one. The numerical value assigned to these factors is usually the results of consumer surveys. In this case, it was the best judgment of the S1-Consumer Reports team.

Appendix D, Table 3 – Convenience Score Transformation for GNE Filters

MODEL	Incovenience			Convenience				Overall Convenience Score
	Feature			Feature				
Stainless Steel Water Container (Expresso)	Claims to require 15 days before full flow (Never saw this increase)							-5
Christella Plus (TATA Swach)				Pre-filter	Auto shut off mechanism	Pure power indicator on the bulb		10
Pureit Classic 14L (Hindustan Unilever)	The pre-filters need to be cleaned periodically	The water flows and stops periodically	There are many places inside the filter where water can stay and contaminant stack	Pre-filter	Auto shut off mechanism	Life indicator	Compact design	2
LifeStraw (Prestige)				Pre-filter				5
AQUASURE AMRIT WITH KITANU MAGNET (EUREKA FORBES)				Pre-filter	Natural shut off			8
KENT Gold UF Membrane Filter	Requires user to pour water in ver slowly and then only up to 5 liters							-5
Swach Smart (TATA) 1500 liters				Pre-filter	Auto shut off mechanism	Pure power indicator on the bulb		10
Swach Smart (TATA) with Silver NANO 3000 liters				Pre-filter	Auto shut off mechanism	Pure power indicator on the bulb		10

Each Inconvenience Feature	Pre-filter	Auto shut off mechanism	Pure power indicator on the bulb	Compact design
-5	5	3	2	2

Defining the Attribute Weightings: The numerical value assigned to these factors is usually the result of consumer surveys. In this case, it was the best judgment of the S1-Consumer Reports team. The attribute weightings to compute the overall score for the GNE filters are shown in Appendix Table D.1.4.

Appendix D, Table 4 – Attribute Weightings for GNE Filters

Attribute	Flow Rate	*E.coli* LRV	Turbidity Removal	TDS Removal	Lifetime
Weighting (%)	50	10	20	0	20

Computing the overall score: The final step to developing the Consumer Reports-style comparative ratings chart is to compute the "overall score" for each filter model tested.

As shown in Appendix Table D.1.5, for each filter model, we sum the multiplication of each attribute score with its associated weighting. Then, the Convenience Score is added to this sum. The result of this computation is shown in the column of "Raw Score."

Appendix D, Table 5 – Overall Final Score for GNE Filters

MODEL	Clean Water Flow Score	*E.Coli* LRV Score	Turbidity Reduction	Hardness Reduction	Lifetime Score	Convenience Score	Raw Score	Final Score
Stainless Steel Water Container (Expresso)	0.81	4.00	5.41	0.0	0.50	-5.00	263	43
Christella Plus (TATA Swach)	2.48	1.75	3.00	0.0	5.00	10.00	285	47
Pureit Classic 14L (Hindustan Unilever)	2.20	4.00	5.43	0.0	1.06	2.00	310	52
LifeStraw (Prestige)	1.31	4.00	5.42	0.0	1.50	5.00	304	51
AQUASURE AMRIT WITH KITANU MAGNET (EUREKA FORBES)	2.50	4.00	5.44	0.0	1.60	8.00	333	56
KENT Gold UF Membrane Filter	2.05	4.00	5.41	0.0	1.09	-5.00	300	50
Swach Smart (TATA) 1500 liters	2.14	2.00	4.50	0.0	4.43	10.00	316	53
Swach Smart (TATA) with Silver NANO 3000 liters	1.61	2.50	5.39	0.0	2.66	10.00	307	51
PHONY MODEL#1 TO TEST CALC	5.49	5.49	5.49	5.50	5.49	12.00	561	100
PHONY MODEL#2 TO TEST CALC	0.5	0.50	0.50	0.50	0.50	-10.00	40	0

For example, the raw score for the Expresso filter is computed as:

$0.81 \times 20 + 4.00 \times 20 + 5.41 \times 30 + 0.0 \times 10 + 0.50 \times 20 - 5 = 263$

Another computation determines the maximum and minimum scores possible as marked blue in this table. A linear transformation is made of these maximum and minimum values to arrive at the scoring range of 100 and 0, respectively.

Final Score = Raw Score$\times$0.192-7.67

The final score for the Expresso filter is: $263 \times 0.192 - 7.67 = 43$.

Developing the ratings chart: Finally, for each attribute, we not only list the attribute score of each filter model, but also assign it an icon according to its performance. In this way, the consumers can more easily judge the filter's performance for each specific attribute. The icons are assigned linearly for scores from 0.5 (poor) to 5.49 (excellent).

Appendix D, Table 6 – Transformation from Scores to Icons

Performance	Icon	Clean Water Flow	*E.Coli* Removal	Turbidity Reduction	Hardness Reduction	Lifetime	Convenience
Excellent:	●	4.49~5.49	4.49~5.49	4.49~5.49	4.49~5.49	4.49~5.49	7.6~12
Very Good:	◕	3.49~4.49	3.49~4.49	3.49~4.49	3.49~4.49	3.49~4.49	3.2~7.6
Good:	◑	2.49~3.49	2.50~3.49	2.50~3.49	2.50~3.49	2.50~3.49	-1.4~3.2
Fair:	◔	1.49~2.49	1.49~2.49	1.49~2.49	1.49~2.49	1.49~2.49	-5.6~-1.2
Poor:	○	0.50~1.49	0.50~1.49	0.50~1.49	0.50~1.49	0.50~1.49	-10~-5.6

Scorings for reverse osmosis filters: For reverse osmosis filters, we only tested two models to their end-of-life. RO filters have another attribute—waste flow—which GNE filters do not have. Thus, a different methodology was used to score and rate those filters. In our work, the S1-Consumer Reports team made judgments based on their expert assessment. The clean flow rate, turbidity removal, TDS removal, and *E.coli* LRV transformation method are the same as those for GNE filters. But in judging the wastewater flow, it would have been inappropriate to say that there should be no wastewater for an "Excellent" icon since generating wastewater is an inherent property of the RO filter. Also, a significant difference was seen between the two models, and this wastewater difference is presented to the consumer by increasing the Tata Swach Platina by one icon category. Choosing a score of 3 for the Clean Water filter model assumed that an average RO filter would generate around 38 L/hr. The situation was the same for Lifetime scoring and Convenience scoring.

Defining the attribute weightings: The attribute weightings to compute the overall score for the reverse osmosis filters are different from those used for GNE filters. The following table shows the attribute weightings for the RO filters.

Appendix D, Table 7 – Attribute Weightings for the RO Filters

Attribute	Clean Flow	% Recovery	*E.coli* LRV	Turbidity Removal	TDS Removal	Lifetime
Weightings (%)	20	20	20	10	10	20

Developing the ratings chart: This process is similar to the one for developing an RO and GNE Ratings Chart.

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REFERENCES

Aspan, Maria. "Consumer Reports to Add Shopping Magazine," *The New York Times* (The New York Times Company), 2006. http://www.nytimes.com/2006/07/24/business/media/24consumer.html (accessed Dec. 15, 2014)

Baker, R.W., *Membrane technology and applications*. Third edition; John Wiley & Sons: Chichester, West Sussex; Hoboken, 2012; p. xiv, 575 p.

Bounds, Gwendolyn. "Meet the Sticklers." *The Wall Street Journal*, 2010.

Bruce, I.D.; Sharon O.S., Drinking Water Treatment: Reverse Osmosis. *NebGuide* 2014.

Central Intelligence Agency. "India," *The World Factbook*. https://www.cia.gov/library/publications/the-world-factbook/geos/in.html (accessed Nov. 15, 2014)

Colwell, R.R.; Huq, A.; Islam, M.S.; Aziz, K.M.; Yunus, M.; Khan, N.H.; Mahmud, A.; Sack, R.B.; Nair, G.B.; Chakraborty, J.; Sack, D. A.; Russek-Cohen, E., Reduction of cholera in

Bangladeshi villages by simple filtration. *Proceedings of the National Academy of Sciences of the United States of America* 2003, 100 (3), 1051–5.

Consumer Reports. *Water Filters*. Consumer Reports. Yonkers, N.Y., May 2010.

Devangee S.; Kinjal B.; Jain N.K.; Modi H.A., Physicochemical Analysis of Water from Various Sources and Their Comparative Studies. *IOSR Journal of Environmental Science, Toxicology, and Food Technology* (IOSR-JESTFT) e-ISSN: 2319-2402, p-ISSN: 2319-2399. Volume 5, Issue 3 (Jul.–Aug. 2013), pp. 89–92.

Dies, R.W., Development of a Ceramic Water Filter for Nepal. Master Dissertation, Massachusetts Institute of Technology, Cambridge, MA, 2003. http://web.mit.edu/watsan/docs_theses_nepal.html (accessed Oct. 25, 2014)

Eisenberg, T.N.; Middlebrooks, E.J., *Reverse osmosis treatment of drinking water*. Butterworths: Boston, 1986; p. vii, 271 pp.

Howard, G.; Bartram J., Domestic water quantity, service level, and health. Geneva: World Health Organization, 2003.

India Center for Science and Environment. Tata uses nano technology for water purifier. http://www.cseindia.org/node/852 (accessed Nov. 22, 2014)

Kubitschek, H.E., Cell volume increase in *Escherichia coli* after shifts to richer media. *Journal of bacteriology* 1990, 172(1), 94–101.

Levin, M.M. Diarrheal disease in infants and young children in developing countries. *Global enteric multi-center study*, 2009. Presentation at Global Vaccine Forum, Bamako, Mali.

Lichtenthaler, H., and Singleton, P. Bacteria in Biology, Biotechnology, and Medicine. John Wiley and Sons, 1999.

Liu, S. Adapting Consumer Reports' Product Evaluation Methods for Particle Removal, Gravity Non-Electric, and Reverse Osmosis Water Filters in the India Marketplace. Masters of Science in the Civil and Environmental Engineering Dept., Massachusetts Institute of Technology, Cambridge, MA, 2015.

Mattson, J.S., and Mark, H.B. Activated carbon: surface chemistry and adsorption from solution. 1971. New York: M. Dekker. pp. 209–221.

Murcott, S.; Hansen, A.; Knutson, J.; Parikh, V.; Tanphanich, J.; Urmi, T.; Wong, T.K.; Water Filter Evaluation Suitability (S1-India) Team Report. 2014, pp. 26–27.

NSF. NSF/ANSI Standard 42 Drinking Water Treatment Units—Aesthetic effects. 2011(a).

NSF. NSF/ANSI Standard 42 Drinking Water Treatment Units—Health effects. 2011(b).

PATH. User Testing of Household Water Treatment and Storage Products in Andhra Pradesh, India, 2011. http://www.path.org/publications/files/TS_swp_user_testing_rpt.pdf (accessed Oct. 24, 2014)

Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Nandagopal, S., Water resources: agricultural and environmental issues. *BioScience* 2004, 54 (10), 909–918.

Ratnayaka, D.D., Johnson, M., and Brandt, M.J., *Twort's Water Supply.* Fifth edition; IWA Publishing. London, 2000.

Sagara, J., Study of Filtration for Point-of-use Drinking Water Treatment in Nepal. Master Dissertation, Massachusetts Institute of Technology, Cambridge, MA, 2000. http://web.mit.edu/watsan/Docs/Student%20Theses/Nepal/Sagara2000.pdf (accessed Nov. 15, 2014)

Singleton P., *Bacteria in Biology, Biotechnology, and Medicine* (Fifth edition). Wiley: Chichester 489 pp. (ISBN 0-471-98880-4 Paperback). pp. 444–454.

USEPA. Quality Criteria for Water. 1976. http://water.epa.gov/scitech/swguidance/standards/criteria/current/upload/2009_01_13_criteria_redbook.pdf (accessed Nov. 10, 2014)

WHO & UNICEF. Progress on Drinking Water and Sanitation. 2014. http://www.who.int/water_sanitation_health/publications/2014/jmp-report/en/ (accessed Nov. 15, 2014)

World Health Organization. WHO International Scheme to Evaluate Household Water Treatment (HWT) Technologies: Procedure for Evaluation ["the Procedure"]. World Health Organization: Geneva, 2014(a).

World Health Organization. WHO International Scheme to Evaluate Household Water Treatment Technologies Harmonized Testing Protocol: Technology Non-Specific. ["the Scheme"]. World Health Organization: Geneva, 2014(b).

World Health Organization. *Household water treatment and safe storage*. 2014(c). http://www.who.int/household_water/en/ (accessed Oct. 25, 2014)

World Health Organization, UNICEF. *A toolkit for monitoring and evaluating household water treatment and safe storage programs.* World Health Organization, 2012. http://www.who.int/household_water/WHO_UNICEF_HWTS_MonitoringToolkit_2012.pdf (accessed Oct. 25, 2014)

World Health Organization. Evaluating Household Water Treatment Options: Health-based targets and microbiological performance specifications. World Health Organization: Geneva, 2011(a).

World Health Organization. *Guidelines for Drinking-Water Quality.* (Fourth edition.) World Health Organization, 2011(b).

World Health Organization. *Guidelines for Drinking-Water Quality*. (Second edition.) Volume III, Surveillance and Control of Community Water Supplies. World Health Organization, Geneva, 1997.

World Health Organization. Total dissolved solids in drinking water. Background document for development of *WHO Guidelines for Drinking Water Quality*. World Health Organization: Geneva, 1996.