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A critical review of point-of-use drinking water treatment in the United States

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Ensuring safe water supply for communities across the United States is a growing challenge due to aging infrastructure, impaired source water, strained community finances, etc. In 2019, about 6% of public water utilities in the U.S. had a health-based violation. Due to the high risk of exposure to various contaminants in drinking water, point-of-use (POU) drinking water treatment is rapidly growing in popularity in the U.S. and beyond. POU treatment technologies include various combinations of string-wound sediment filters, activated carbon, modified carbon, ion exchange and redox media filters, reverse osmosis membranes, and ultraviolet lamps depending on the contaminants of concern. While the technologies are well-proven, highly commoditized, and cost-effective, most systems offer little in the way of real-time performance monitoring or interactive technology like other smart home appliances (e.g., thermostats, smoke detectors, doorbells, etc.). Herein, we review water quality regulations and violations in the U.S. as well as state-of-the-art POU technologies and systems with an emphasis on their effectiveness at removing the contaminants most frequently reported in notices of violations. We conclude by briefly reviewing emerging smart water technologies and the needs for advances in the state-of-the-art technologies. The smartness of commercially available POU water filters is critiqued and a definition of smart water filter is proposed.

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INTRODUCTION

Access to clean water is of utmost importance for human health and society at large. References to water purification and filtration methods can be traced back to ancient Sanskrit and Egyptian writings—including descriptions of boiling, solar heating, and sand filtration¹. Hippocrates, often referred to as the “father of medicine,” found that water could be made purer by filtering it and, in 500 BC, he designed a simple sediment filter by running water through cloth². In modern times, sand filters were first documented as a water treatment device in 1804. By 1852, the Metropolis Water Act in London required the use of sand filters in part of the city³. The filters removed suspended solids, but did not address pathogenic microorganisms or chemical contaminants since microbiology and analytical chemistry were not yet adequately established⁴. In the United States, drinking water standards were gradually developed over the 20th century, culminating in the passage of the Clean Water Act (1972) and the Safe Drinking Water Act (1974), which were part of a landmark decade of promulgating new environmental regulations.

Water quality can be broken into numerous physical, biological, and chemical components⁵. Physical water quality descriptors include turbidity, total, settleable, filterable and dissolved solids, color, taste, odor, and temperature. Biological quality refers to protozoan, bacterial, and viral pathogens. Biological contamination is often an immediate health risk: crippling outbreaks of typhoid, cholera, salmonella, and other diseases have been spread through contaminated water supplies. Chemical components include trace organic and inorganic compounds, which may be toxic to humans and can also cause discoloration, poor taste, or odor⁶. Toxic chemicals may lead to both acute and chronic health effects. Water quality regulations in the U.S. were developed to

address all three classes of contaminants. Primary drinking water standards are defined by maximum contaminant levels (MCLs) established by the U.S. Environmental Protection Agency (EPA)⁷. The standards focus on biological and chemical contaminants. The trace chemical contaminants are sometimes less than one part per billion and may be set at or near the limits of analytical detection methods⁷. Physical water quality components are mainly covered by the U.S. EPA's secondary drinking water standards, which are unenforced unlike their primary counterparts⁸.

Although water quality is well-regulated in the U.S., there is considerable variation in contaminant levels by location. Consequently, consumers who are concerned about the quality of their water supply often purchase bottled water or various water-filtration devices to remove any remaining impurities. For instance, a recent set of studies conducted in Los Angeles, CA, USA has determined the following^{9,10}:

- Levels of distrust in tap water are high, especially among households of color (e.g., LA County had 2nd highest level of distrust among urban areas in the country before Flint).
- Equating distrust with misperception in all cases (as many water systems and public health agencies do) is incorrect and generic “education” approaches to improve trust are neither effective nor respectful.
- Much of distrust appears “rational” and stems from past/present experience of unclear, if not unsafe (we draw a distinction here) drinking water, much of it from premise plumbing.
- Solutions to issues of premise plumbing are tough especially due to tenancy split-incentive issues, but legal and especially financial incentive approaches from other sectors can be brought to bear.

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- The consequences of distrust are severe for household health, finances, trust in the government, and the environment.

Since water quality degradation may occur in the distribution system, one solution could be widespread implementation of point-of-entry (POE) water treatment where a POE system is installed at a household's or building's water main intake ahead of the structure's taps, faucets, or other dedicated outlets used to dispense water for drinking, cooking, and bathing. However, degradation can occur in premise plumbing (e.g., copper pipes) in older buildings, and hence, it may make the most sense to deploy point-of-use (POU) water treatment just ahead of the tap, faucet or dispensing outlet. In this review, we focus on POU water treatment.

Typical POU systems contain water treatment technologies such as media filtration, reverse osmosis (RO) membranes, UV disinfection, and remineralization (particularly after RO)¹¹. Large particles, rust, and debris are first removed by filtration through string-wound sediment filters. Next, some form of selective separation may be employed such as redox media, activated carbon (AC), and/or ion exchange (IEX). Membrane technology, most commonly RO, removes nearly all suspended and dissolved contaminants such as dissolved organic chemicals, dissolved metals, minerals, and salts¹¹. UV disinfection inactivates pathogenic microorganisms, rendering them non-infectious¹¹. Remineralization after RO filtration is often used to add back the minerals removed by earlier stages to provide pH-buffered, better-tasting water¹¹. In each step, there are various technologies available with different contaminant removal efficacies to satisfy a variety of situations and needs. In addition, emerging POU treatment technologies such as capacitive deionization (CDI) are attracting attention because of their selective contaminant removal¹².

The rapid development of Internet technologies has encouraged many home-appliance manufacturers to provide "smart" products, including "smart" POU filters. There are various definitions of smart home appliances^{13,14}. The consensus is that if a product is smart, it is one that can be remotely controlled by the user via a smart phone, tablet, or other device. Connectivity and interaction with the user via an "app" is achieved using WiFi or Bluetooth® technology. Smart filter systems take many forms and have differing levels of sensor integration, but information on which filter media and sensors are included in home water treatment systems has been lacking. Moreover, different manufacturers seem to have different views on the smartness of water filters. Some products claim themselves to be "smart" because they can provide water with better quality, which does not satisfy the connectivity requirement of other smart home appliances.

This study reviews U.S. federal and (several) state regulations, the frequency and nature of water quality violations in the U.S., state-of-the-art POU water treatment technologies and their contaminant removal capabilities, especially emerging contaminants. Further, representative commercially available POU systems are compared, making note of filter types, any sensors employed, expected service life, and other details. Finally, the smartness of commercially available POU water filters is critiqued and a definition of smart water filter is proposed.

WATER QUALITY REGULATIONS, VIOLATIONS, AND HAZARDS IN THE US

Access to clean drinking water is imperative because of the potential for both acute and chronic health risks associated with drinking contaminated water. Federal regulations serve the purpose of reducing the likelihood of becoming ill from drinking the tap water. The EPA regulates contaminants by establishing MCLs for microbiological, organic, and inorganic contaminants based on health guidelines, research, and feasibility¹⁵. These standards delineate the maximum amount of a contaminant that

can be allowed in drinking water to minimize exposure. States may build on the EPA's standards by adding additional contaminants not regulated at the federal level and by further reducing MCLs for federally regulated contaminants.

Federal drinking water regulations

To regulate drinking water, the EPA establishes primary and secondary drinking water standards. Primary standards are enforceable by law and apply to all the U.S. public water systems; their goal is to limit levels of harmful contaminants in drinking water. The EPA¹⁵ has a list of 88 contaminants regulated in the primary standards with the following contaminant categories and numbers: 3 disinfectants, 4 disinfection byproducts (DBPs), 16 inorganic chemicals, 8 microorganism categories, 53 organic chemicals, and 4 radionuclides. The EPA regulates most of these contaminants by establishing MCLs that can be present in the effluent of drinking water treatment plants. These MCLs are intended to keep people safe, but they are not necessarily safe. The maximum contaminant level goal (MCLG) is the amount of a contaminant in drinking water at which there is no known or expected risk. MCLs are determined by feasibility of measurement, removal, and enforcement in combination with MCLGs, so there may be some health risks even with MCLs in place.

To supplement the enforced primary standards, the EPA sets unenforced secondary drinking water standards. They are intended to improve aesthetic qualities of water such as taste, color, and odor. According to the EPA, these standards are important because if water looks, tastes, or smells bad, people may not drink it even if it is perfectly safe. Some other secondary standards help control scaling, which restricts water flow and corrosion, which can cause pipes to wear out or dissolve harmful contaminants previously fixed within the mineral scale⁸.

The EPA also maintains a contaminant candidate list (CCL) for compounds that are not currently regulated but are expected to be found in public water systems and may require regulation in the future¹⁶. The CCL serves an essential purpose in the process of enacting water quality regulations. Every 5 years, the EPA decides if it will regulate or not regulate at least five contaminants on the CCL. In February 2020, the EPA made preliminary decisions to regulate perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), but not to regulate six other chemicals including dichloroethane and acetochlor¹⁷. They make these decisions using data collected about these contaminants and compare it to the criteria for regulation under the Safe Drinking Water Act (SDWA). The CCL must be updated every 5 years, and the contaminants with the greatest potential health risks in drinking water shall be placed on the list¹⁶. Once the EPA decides to regulate a contaminant, it can take years before a regulation is enacted. For example, the EPA decided to regulate perchlorate in 2011, but as of 2020, the EPA still has not set a MCL for perchlorate¹⁸. Because it takes many years to regulate a chemical that it deems to be unsafe for human consumption¹⁹, there may be chemicals present in drinking water for which negative healthy effects are known, but no action has yet been taken.

State drinking water regulations

States are required to have standards at least as strict as EPA standards for primary drinking water treatment²⁰. Yet, state standards may vary from the EPA standards, providing room for states to regulate certain contaminants more strictly or address contaminants that are not yet federally regulated^{21,22}. For example, in California, contaminants are regulated because of determinations made by the California Office of Environmental Health Hazard Assessment, which sets public health goals based on the health impacts of individual contaminants^{23,24}. For carcinogenic contaminants, they create regulations based on the risk of cancer from exposure to different amounts of the

Table 1. Size of public water system by population served³⁰.

Size of public water system	Population served
Very small	500 or less
Small	501–3300
Medium	3301–10,000
Large	10,101–100,000
Very large	More than 100,000

contaminant. Typically, the acceptable risk is for—at most—one person in a million to get cancer upon exposure over 70 years. After proposing a standard based on current research, they consult a group of scientific experts, make further revisions, and finally allow public comment. After setting a goal, they can establish an enforceable standard that is as close as possible to the goal while considering economic and technical feasibility. This process is similar to how the EPA sets its MCLs, but because it is separate from the EPA, they can regulate chemicals of local concern such as agricultural contaminants²⁵.

Table S1^{7,26–28} compares the EPA's primary drinking water standards to the drinking water regulations of several states; it also displays the health effects of exposure and the origins of these contaminants. Alaska, Texas, and California exhibit an exemplary range of different state's approaches to regulations, with California being the most stringent²⁹. Exposure to regulated contaminants can cause a variety of health issues including cancer, kidney problems, nervous system problems and more, which is why these chemicals are regulated by the EPA and states. In addition, one clear commonality amongst the origins of these contaminants is that they frequently come from industrial operations that discharge waste into the environment.

Violations of standards

Even though regulations exist to limit exposure to toxic contaminants, sometimes public water utilities violate existing standards. Public water utilities are categorized by the EPA as community water systems (CWSs), transient non-community water systems (TNCWSs), or non-transient non-community water systems (NTNCWSs) (Fig. S1). The EPA then classifies the size of these public water systems in categories of very small, small, medium, large, and very large (Table 1)³⁰. Fig. S2³⁰ displays the amount of each type of public water system by size. It can be seen that CWSs represent a larger percentage of public water systems as the size of the population served increases, which means they end up serving residential communities, whereas smaller public water systems tend to be TNCWSs.

The EPA publishes a database with information about the types and sizes of public water systems and the violations that occur within these public water systems. Violations required to be reported under SDWA of EPA are grouped into the following categories³¹:

1. Health-based, including 3 categories: (1) exceedances of the maximum contaminant levels (MCLs) which specify the highest allowable contaminant concentrations in drinking water, (2) exceedances of the maximum residual disinfectant levels (MRDLs), which specify the highest concentrations of disinfectants allowed in drinking water, and (3) treatment technique requirements, which specify certain processes intended to reduce the level of a contaminant³¹.
2. Monitoring and reporting: failure to conduct regular monitoring of drinking water quality, or to submit monitoring in time, as required by SDWA³¹.
3. Public notice: systems are required to alert consumers if there is a serious problem with their drinking water or if

Table 2. Serious violators in 2019³⁰.

Size of treatment plant	Number of treatment plants	Number of serious violators	Average size of violator	Population affected
Very small	119,848	3724	123	460,294
Small	18,832	620	1361	844,246
Medium	5269	181	5592	1,012,249
Large	3965	113	26,718	3,109,218
Very large	443	12	308,364	3,700,372
Total	148,357	4650	1943	9,036,379

Note: For Table 3, size of treatment plant refers to the population affected as indicated in Table 1.

there have been other violations of system requirements, as required by SDWA³¹.

4. Others: violations of other requirements of SDWA, such as failing to issue annual consumer confidence reports³¹.

Table 2 shows the number of serious violations by treatment plant size. A serious violation is when a public water system has unresolved serious, multiple, and/or continuing violations, which need to be returned to compliance or the system will be faced with formal enforcement action³⁰. Many serious violators have violated monitoring and reporting guidelines; they fail to regularly monitor drinking water quality or promptly submit monitoring results to the EPA or a public health agency³². These violations indicate mismanagement or neglectful monitoring rather than an immediate health hazard.

However, some violations are health-based violations where public water systems exceed MCLs, maximum residual disinfectant levels, or have an incorrect treatment technique that is put in place to remove certain contaminants³⁰. Especially, those violations that can pose immediate health effects are called acute health-based violations. There were over 6.5 million people affected by health-based violations in the United States in 2019. Violations including exceeding monthly allowed turbidity levels, treatment technique violations, *Escherichia coli* present in treated water, and nitrate violations have been reported³⁰.

Allaire et al.³³ evaluated spatial and temporal patterns in health-related violations of the SDWA using a panel dataset of 17,900 CWSs from 1982 to 2015. About 21 million people are affected by health-based water quality standard violations in the year 2015, according to the study³³.

During each year between 1982 and 2015, 9–45 million people, up to 28% of US population, were affected³³. Health-based violation was observed in about 8.0% of the 608,600 utility-year observations, while total coliform violation is observed in about 4.6% of all observations³³. In total, 95,754 health-based violations were observed, and 37% of all violations are the total coliform type (Fig. 1a). About 36% of violations are categorized as “other” contaminants, primarily DBPs. While violations of treatment rules and nitrate are less commonly observed (21% of total)³³.

The number of violations per CWS (Fig. 1b) differs between rural and urban areas. Rural areas have a larger compliance gap than suburban and urban areas, however, fewer violations with DBP violations were observed in rural areas with higher incomes³³. Differences between rural and suburban areas were exaggerated after new DBP rules in the early 2000s³³, corresponding to the spike in Fig. 1b. Due to limited financial resources and technical expertise, regulatory compliance is a challenge for rural systems³³. In contrast to large systems, small systems face restricted access to loans and outside financing³⁴. Moreover, smaller customer base

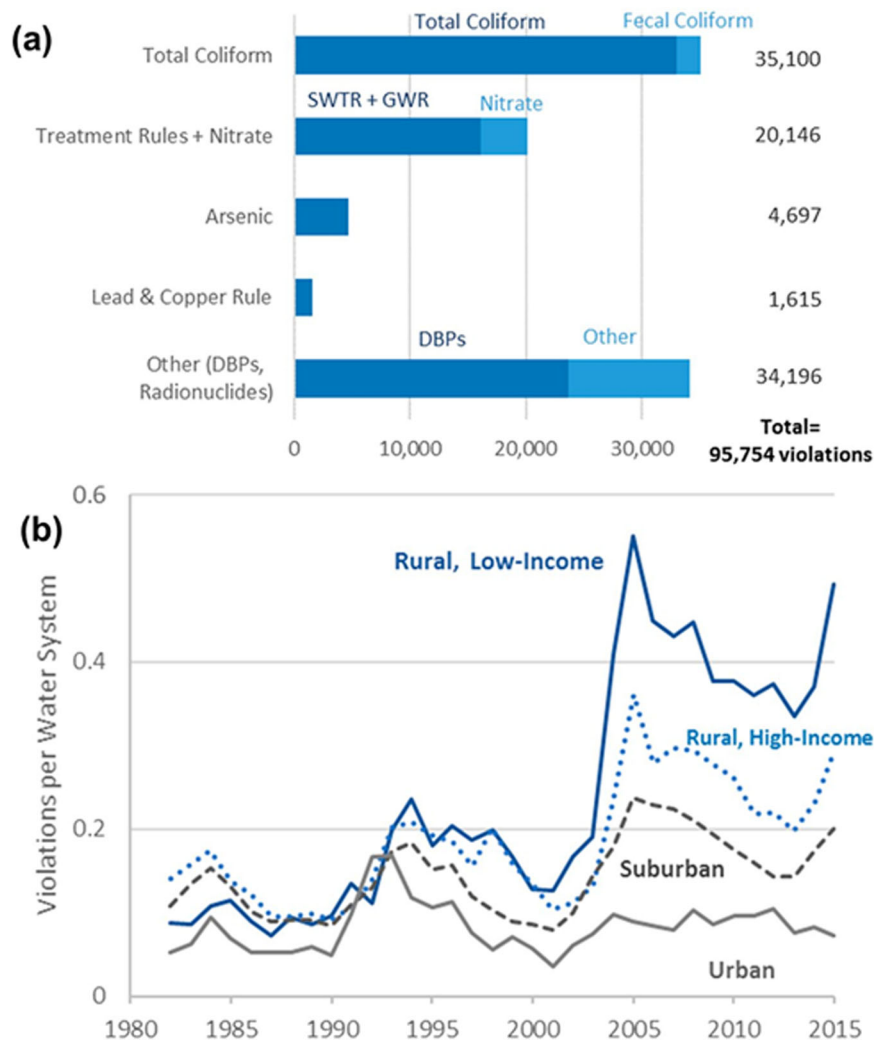


Fig. 1 Health-related violations of the Safe Drinking Water Act. a Number of health-based violations, and **b** total violations per water system. In total, 95,754 health-based violations were observed from 1982 to 2015, affecting up to 28% of US population. Rural areas have a larger compliance gap than suburban and urban areas; however, fewer violations with DBP violations were observed in rural areas with higher incomes (reprinted with permission from³³; Copyright© PNAS, 2018).

has less revenue for infrastructure improvements, repayment of debt, and salaries to attract technically skilled operators³⁴. All these factors make the rural system operations and development challenging, and eventually may trigger the violations.

Violations also vary geographically. The distribution of the total number of violations, from 1982 to 2015, per CWS in a given county is shown in Fig. 2A. The majority of violations are observed in rural areas, located in Texas, Oklahoma, and Idaho. Total coliform violations, as shown in Fig. 2B, are primarily observed in the West and Midwest. Differences of violations across counties can be attributed to the difference of quality of source water as well as the state-level enforcement³³. Other factors such as different temperatures at different seasons can also contribute to the regional difference of violations across the U.S. For instance, high summer temperatures might cause the Southwest region to be particularly susceptible to DBP violations. SDWA violations are mostly identified in Oklahoma and parts of Texas, based on local spatial autocorrelation, shown in Fig. 2C. 11% of the CWSs have repeat violations, including two or more subsequent years of a violation³³. The states with the greatest proportion of CWSs with repeat violations are Oklahoma (43% of CWSs in the state), Nebraska (35%), and Idaho (33%)³³.

Table S4 shows the breakdown of the size of treatment plants and the source of water. Larger treatment plants tend to use surface water, whereas smaller treatment plants predominantly use groundwater. From the above table and information about the different types and sources of violations of drinking water treatment plants, the percentage of violations by water source can be determined. The values in Table S5 were computed using the number of surface water and groundwater violations by size and comparing that to the total number of treatment plants using either surface water or groundwater as a source by size (data from Table S4). The percentages of CWSs, NTNCWSs, and TNCWSs were computed as well, using the number of violations of those types by size and comparing that to the total numbers of treatment plants by type and size (data from Table S4). Table S5 shows that with every type of violation, treatment plants that use surface water as a source tend to have a higher percentage of violations than treatment plants that use groundwater as a source. As the size of the treatment plant increases, the percent of violations amongst public water systems that use surface water tends to decrease. The only exception seen here is for treatment plants of very large size. In addition, CWSs typically have slightly higher percentages of violations (Table S5). This analysis, presented in

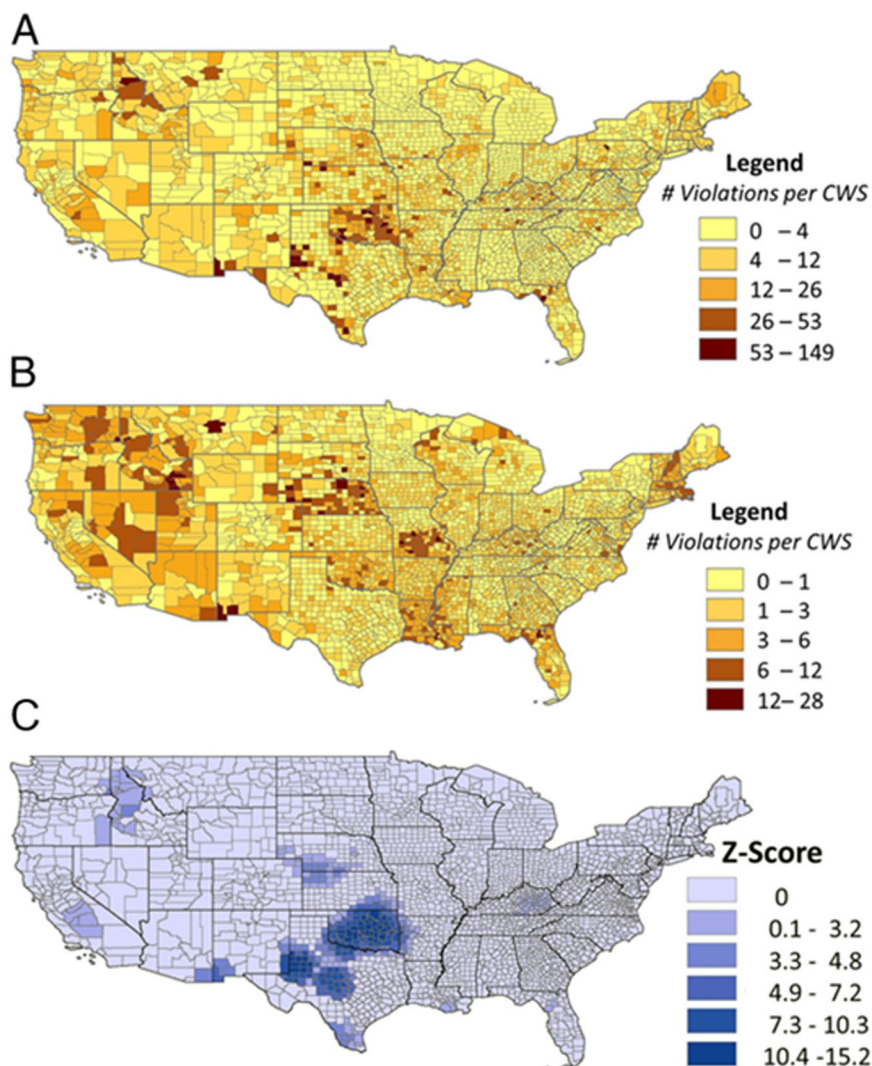


Fig. 2 Distribution of the total number of violations per CWS. **A** Total violations. **B** Total coliform violations. **C** Spatial clusters (hot spots) of health-based violations, 1982–2015. Violations also vary considerably across geographic locations. Some of the counties with the highest prevalence of violations are rural, located in Texas, Oklahoma, and Idaho (reprinted with permission from³³, Copyright© PNAS, 2018).

Table 3, shows that CWSs tend to have a higher percentage of surface water sources compared to NTNCWSs and TNCWSs.

Non-grid-tied water resources

Domestic wells (private or homeowner wells) are the dominant source of drinking water for people living in rural parts of the United States³⁵. Population distribution using domestic supply wells per square kilometer is shown in Fig. 3a. Over 43 million people, 15% of the U.S. population, rely on domestic (private) wells as their source of drinking water³⁶. These private wells are not regularly tested for known contaminants, and thus, may pose unknown health risks. The water safety of domestic wells is not regulated by the Federal Safe Drinking Water Act or, in most cases, by state laws. Instead, individual homeowners are responsible for maintaining and monitoring their own wells³⁶.

In a study of 2100 domestic wells, water in about 20% of the wells is contaminated with one or more contaminants at a concentration greater than MCLs^{35,36}. Table 4 summarized some common contaminants in domestic wells which frequently exceeding health standards (MCLs regulated by USEPA or U.S. Geological Survey (USGS) Health-Based Screening Levels) in tests. The most common contaminants that were found to exceed health standards were metals including lead and arsenic,

radionuclides, and nitrates³⁷. Nitrates in drinking water supplies can cause harm such as methemoglobinemia in young children, but nitrates rarely cause direct harm to adults³⁶. Microbial contaminants (for example, bacteria) were found in about 30% of wells tested, about 400 wells in total³⁶. Ayotte et al.³⁵ developed a logistic regression model of the probability of having arsenic >10 µg/L (“high arsenic”) from 20,450 domestic wells in the U.S. As shown in Fig. 3b, approximately 2.1 million people in the conterminous U.S. were using water from private wells with predicted arsenic concentration >10 µg/L³⁵. Some states have both relatively large population, over 1 million people, and high percentages, over 1%, of total state populations with arsenic >10 µg/L. It is noteworthy that 60% of all counties with the largest population with high-arsenic wells are located in New England; other top-10 counties are located in Ohio, North Carolina, California, and Idaho, respectively³⁵. Considering the high risk of exposure to the various contaminations, it is therefore imperative to apply additional treatments, such as POU, before using the well water in households.

Contaminants of emerging concern with no regulations

Contaminants of emerging concern (CECs) are chemicals or microorganisms that are not commonly monitored in drinking

Table 3. Type of system vs. source in different size of treatment plants³⁰.

Size of treatment plants	Type of system	Groundwater source	Percent groundwater source	Surface water source	Percent surface water source
Very small	CWS	24,139	88.4	3006	11.6
	NTNCWS	14,656	96.5	505	3.5
	TNCWS	75,139	97.1	2094	2.9
	Total	113,934		5605	
Small	CWS	9696	72.5	3659	27.5
	NTNCWS	2255	91.1	204	8.9
	TNCWS	2823	94.7	152	5.3
	Total	14,774		4015	
Medium	CWS	2791	55.5	2240	44.5
	NTNCWS	102	62.6	61	37.4
	TNCWS	59	78.7	16	21.3
	Total	2952		2317	
Large	CWS	1505	38.5	2409	61.5
	NTNCWS	19	50.0	19	50.0
	TNCWS	9	69.2	4	30.8
	Total	1533		2432	
Very large	CWS	74	16.8	367	83.2
	NTNCWS	0	0	1	100
	TNCWS	0	0	1	100
	Total	74		369	

water because they do not have established MCLs³⁸. A USGS study found that over 80% of streams in the U.S. contained some form of emerging contaminant including pharmaceuticals, hormones, detergents, plasticizers, fire retardants, pesticides, and more. Although these were generally found at low concentrations, a growing number of research report their close relationships with some human diseases^{39,40}. In addition, a more recent study found that about 8% of groundwater sources used for drinking water contain hormones and pharmaceuticals⁴¹. The unregulated status of these contaminants makes them unmonitored by treatment plants in many cases. It is also unknown how much of them end up in drinking water after drinking water treatment. Thus, there is potential health risk for people consuming these contaminants in drinking water.

Table 5 shows the features of several typical CEC types in drinking water. *N*-Nitrosodimethylamine (NDMA) is a semi-volatile organic compound used to help produce liquid rocket fuel, antioxidants, and additives for lubricants. Animal studies have found that NDMA causes cancer in the liver, respiratory tract, kidneys, and blood vessels³⁹. NDMA is also expected to be carcinogenic to humans⁴², while EPA has not set a MCL for NDMA yet. However, it has been placed on the fourth contaminant candidate list (CCL4). Also, several states have guidelines (not regulations) for levels of NDMA that could exist in water. In California, several nitrosamines have guidelines set that were above a specified level (in the instance of NDMA, 300 ng/L), and a response is recommended. Potential treatments for NDMA include photolysis with UV radiation⁴³, biological treatment, microfiltration, and RO treatment. Despite these treatments, it may still be present in water because it is a byproduct of chlorination, which occurs after treatment³⁹.

Pharmaceutical and personal care products (PPCPs) are commonly found in sources of drinking water and enter these sources through domestic wastewater, hospital discharges, improper manufacturer disposal, and wastewater treatment plants⁴⁴. PPCPs typically enter wastewater through human excrement or bathing and washing activities⁴⁵. The amounts of PPCPs found in these treatment plants is low with concentrations

between ng/L and µg/L. However, their long-term health effects are unknown and they can cause health issues through accumulation in the food chain⁴⁶. In addition, some PPCPs containing amine groups demonstrate the potential to react with chloramines in the disinfection process to form toxic nitrosamines such as NDMA, which is not federally regulated and can cause adverse health effects as stated before⁴⁷.

1,4-dioxane is another concerning contaminant given its classification as a probable human carcinogen. Approximately 30 million people in the U.S. have levels of 1,4-dioxane exceeding the health reference level for cancer, which indicates that it poses a serious risk to human health⁴⁸. It is currently on the EPA's CCL4 and has been on prior CCLs, which indicates 1,4-dioxane's recognition as an emerging contaminant³⁹. The problems with 1,4-dioxane include that it is highly soluble in water and does not react easily with other chemicals. In addition, AC filters do not absorb it. The best-known removal method appears to be RO⁴⁸.

Methyl tert-butyl ether (MTBE) is an additive used in gasoline, designed for more efficient fuel combustion thus to improve overall air quality. It can cause liver, kidney, immune system, testicular, central nervous system, uterine, headache, and lung problems⁴⁰. Like other CECs, no regulations have been established for MTBE by the EPA. In California, an established MCL for drinking water is 13 µg/L and a secondary maximum contaminant level (SMCL) is 5 µg/L⁴⁹. The SMCL was established for water quality aesthetic properties such as taste and odor⁴².

Perfluorinated compounds such as PFOS are extremely hazardous emerging contaminants that enter the environment through their applications in the metal industry, firefighting foam, coatings on paper and textiles, and semiconductor production⁵⁰. They can also occur due to biotransformation of dipolyfluoroalkyl, phosphates, fluorotelomer alcohols, and other chemicals⁵¹. They are persistent in the environment and tend to accumulate in red blood cells⁴⁸. PFCs can cause pancreatic, liver, and Leydig cell cancers⁴⁰. They are frequently found in treated drinking water with levels of up to 1000 ng/L, and over 6 million people receive water from systems that exceed health advisory levels for PFAS⁴⁸. Studies have concluded that people who drink

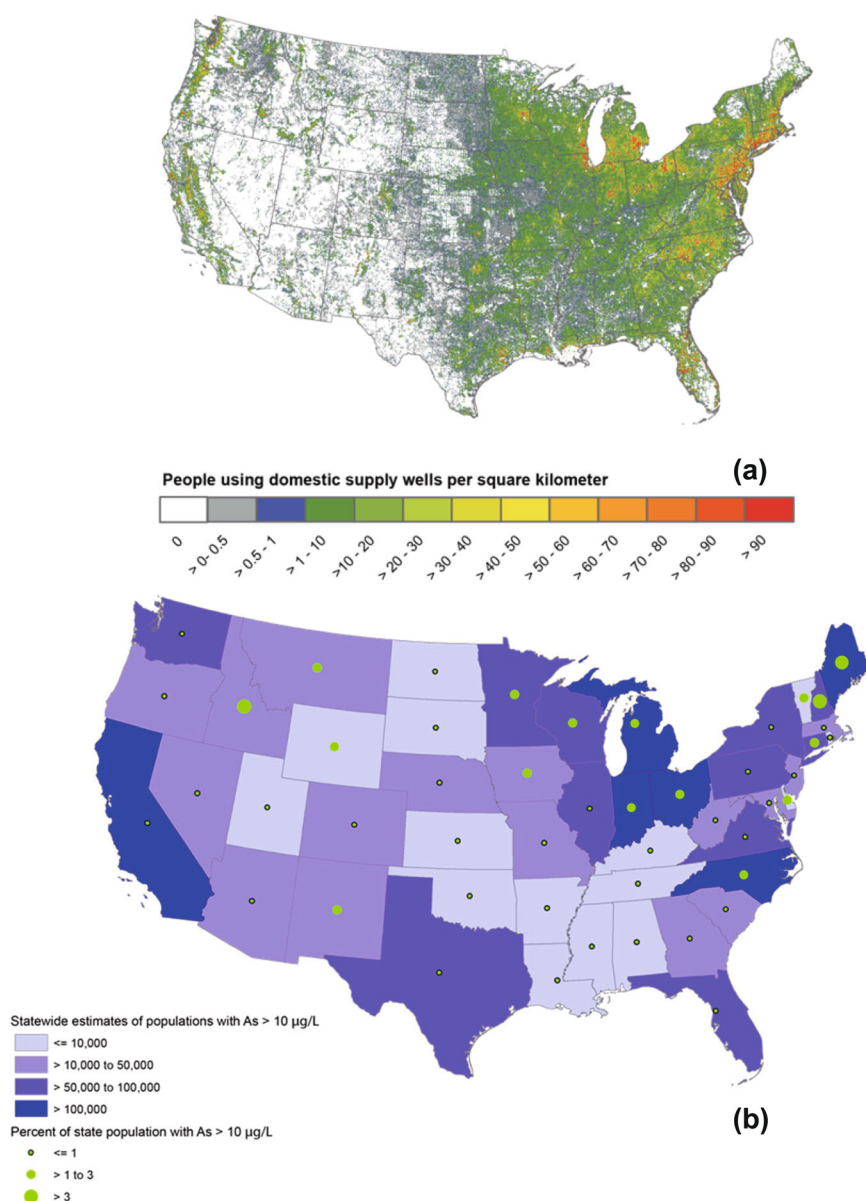


Fig. 3 Distribution of the population using domestic wells. **a** Population using domestic wells, and **b** domestic wells affected by arsenic. Over 43 million people, 15% of the U.S. population, rely on domestic (private) wells as their source of drinking water. About 2.1 million people in the conterminous U.S. were using water from private wells with predicted arsenic concentration >10 µg/L (reprinted with permissions from^{35,36}; Copyright © Elsevier, 2017; Copyright © ACS, 2017).

water with PFAS in it have higher levels of PFAS in their blood, indicating the contaminant's health risk⁴⁸. PFOS are easily removed by using granular activated carbon (GAC) filters which can remove over 90% of them and ROMs which can remove more than 99% of them⁴⁴. The EPA decided in 2020 to regulate PFOA and PFOS in drinking water, but it may take many years before a MCL can be established as was the case with other contaminants taking over 10 years between the decision to be regulated and actual regulation⁴⁴.

Antibiotics are another concerning contaminants that can be found in water. Antibiotics in water can cause the rise of antibiotic-resistant genes and antibiotic-resistant bacteria. This can make the use of antibiotics less effective against human and animal pathogens. As of now, there are approximately 2 million people who die in the U.S. from antibiotic-resistant bacteria per year, which is why it is important for them not to end up in aquatic environments⁴⁸. Antibiotics can be detected at very low

levels across the United States in the sources of drinking water (levels of between 20 and 60 ng/L)⁵². They are rarely detected in treated drinking water, and if they are detected, the levels are even lower (5–20 ng/L), and thus present little risk to human consumption themselves⁵³.

Another concerning area of emerging contaminants is DBPs which are produced when chemical oxidants (e.g., chlorine, ozone, chloramine, etc.) are used for disinfecting microbes in drinking water. Over 700 DBPs have been identified by EPA, while only 11 types are regulated⁴⁸. DBPs have been known to cause cancer and birth defects⁴⁸. Thus, they too pose a risk to human health despite regulations that exist.

In summary, although well-intended and well-developed, the U.S.'s drinking water regulations do not fully assure the quality of tap water to prevent either short-term or long-term illness from drinking it. Improving upon water treatment technologies and moving them closer to the POU is a way to help remove

Table 4. Contaminants in domestic wells exceeding health standards and removal methods.

Contaminant type	Contaminant	Source	Potential health effects	Removal method
Radionuclide	Radon ¹⁸⁴	Breakdown of uranium	Lung cancer	Granular activated carbon (GAC)
Trace element	Strontium ¹⁸⁴	Naturally released from bedrock	Bone disease	Ion exchange (IEX) resin and lime softening
	Lead ¹⁸⁵	Corrosion of plumbing materials	Damage to children's nervous system under low levels of exposure	Reverse osmosis (RO) or carbon filter
Major ions	Arsenic ¹⁸⁴	Natural deposits and agricultural pollution	Carcinogenic to humans	RO
	Manganese ¹⁸⁴	Natural deposits	Neurological disorder	Ion exchanger and RO
	Uranium ¹⁸⁴	Natural deposits	Kidney toxicity and increased risk of cancer	RO
	Boron ¹⁸⁴	Industrial wastes and fertilizer pollution	Skin inflammation and some gastrointestinal effects	Boron-specific IEX resin and RO
	Fluoride ¹⁸⁴	Released from rock to water	Mottled teeth, bone disease	RO
Organic compounds	Dieldrin ¹⁸⁶	Insecticide pollution	Headaches, dizziness, and uncontrollable muscle movements	Activated carbon
	Diazinon ¹⁸⁷	Insecticide pollution	Nervous system health effects, such as stomach pain and vomiting	NH ₂ Cl-induced activated carbon
	Atrazine ¹⁸⁸	Herbicide pollution	Cardiovascular system problems and reproductive problems	GAC
	Alachlor ¹⁸⁹	Herbicide pollution	Eye, liver, kidney problems and increased risk of cancer	GAC
	<i>E.coli</i> ¹⁸⁴	Feces from infected humans or animals	Diarrhea, urinary tract infections, respiratory illness	UV disinfection
Bacteria	Nitrate ¹⁸⁴	Fertilizer pollution	Hematological damage	Ion exchanger and RO
Nutrient				

Note: references for each contaminant are cited at the second column.

contaminants that are not regulated yet or are introduced during distribution from the treatment plant to the tap. GAC, RO, UV radiation, and combinations of the above are all advanced water treatment technologies that remove emerging contaminants effectively. Although there has been much research on the mechanics and removal efficacies of these water treatment technologies, little information is available on their application in POU water treatment.

POU WATER TREATMENT TECHNOLOGIES

POU drinking water treatment systems are installed on the water supply lines ahead of water taps, showers, and dispensers to provide on-site purification of water for drinking, bathing, or cooking. A wide range of POU technologies have emerged in the past two decades including AC, redox media, ROMs, UV disinfection, CDI, and others. They are usually combined in a specific sequence to form a POU system (Fig. 4). The systems are thus expected to remove hazardous contaminants exceeding regulation limits while keeping those substances that are healthy and essential for human health.

Media filtration

Sediment filters. The most basic type of POU filter is the sediment filter, a form of physical filtration. It removes suspended solids from water, such as insoluble iron and manganese, and reduces water turbidity. In Fig. 5, we present a schematic of the flow configuration and a photo of typical string-wound sediment filter⁵⁴. Suspended solids from untreated water will accumulate throughout the depth of the filter material, while dissolved contaminants are not retained. Therefore, the classification and removal efficacy of sediment filters is highly dependent on the pore size of the filter media. For example, a “5 µm” filter is able to capture sediments as small as about 5 µm⁵⁵. In addition, the filter rating is commonly described as either “nominal” or “absolute.” Nominal filters are expected to trap >90% of particles larger than the pore size rating, while absolute filters should trap about >99%.

The string-wound sediment cartridge filter is a common type of POU sediment filter, which is made from a central cartridge wrapped in string (Fig. 5). This type of filter typically has a micron-rating from 0.5 to 200 depending on the diameter of the string. The filter functions by mechanically trapping particles that are larger than the characteristic space between strings; sometimes thinner string is used near the core center and thicker string on the outside. In this way, the string-wound sediment filter can capture particles not only on the cartridge surface, but also through its depth and at the core surface.

The first string-wound filter cartridge entered the U.S. market around the mid-1930s. It was made of a woven wire mesh core surrounded by cotton yarn⁵⁶. Today, this type of cartridge filter has evolved considerably by improving the filter material and the media arrangement. For example, by adding silver ions to the polypropylene yarn, the string-wound filter inhibits the growth of microbes. Also, to be compatible with corrosive solutions or high-temperature fluids, stainless-steel can be used as the core material to enhance the polypropylene stability and prevent it from swelling or softening⁵⁷.

Ion exchange resins. Ion exchange (IEX) is a reversible chemical reaction between compounds in the aqueous phase and fixed charged functional groups on and within a solid phase. Polymeric resins are the most common IEX materials, widely used not only in POU filtration, but also in large-scale water and wastewater treatment, hydrometallurgy, chromatography, and sensors⁵⁸. Although there seem to be a variety of IEX resins for water treatment in the market, they can be roughly categorized into five

Table 5. Features of several CECs in drinking water.

Contaminant type	Human toxicology	Regulation	Removal method
NDMA	Liver damage and cancer ³⁹	No MCL set by EPA, but it is included in CCL4	Photolysis by ultraviolet radiation ⁴³
PPCPs	Stomach and intestine diseases ⁴⁶	None established	Integrated membrane system MBR-RO/NF ⁴⁵
1,4-dioxane	Cancer ³⁹	No MCL set by EPA, but it is included in CCL4	Combined RO and GAC ⁹³
MTBE	Liver, kidney, immune system, testicular, central nervous system, uterine, headache, and lung problems ⁴⁰	None established	GAC; activated oxidation ⁴⁹
PFOA	Pancreas, liver, and Leydig cell cancer ⁴⁰	EPA has decided to regulate PFOA but the levels have not yet been determined	GAC; membrane separation; ion exchange; powdered activated carbon ⁵¹

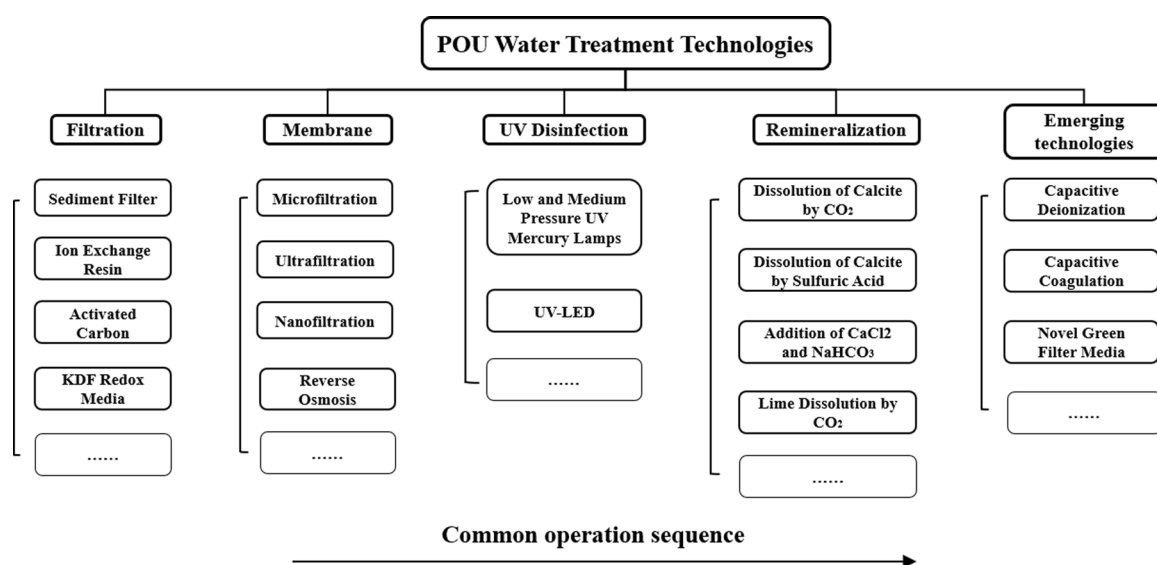
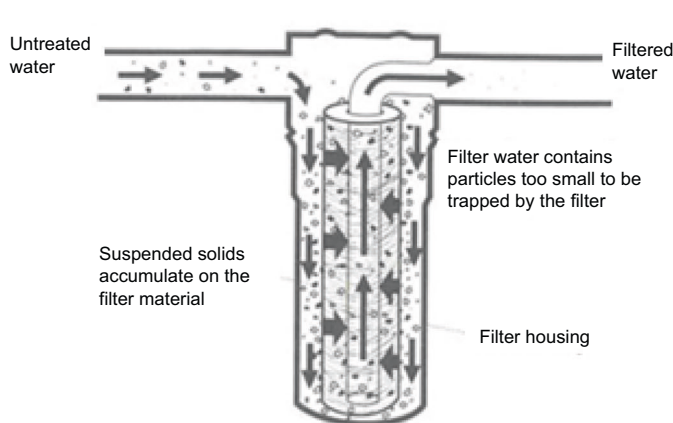
**Fig. 4** Examples of POU water treatment technology sequences. A wide range of point-of-use technologies have emerged in the past two decades including activated carbon, redox media, RO membranes, UV disinfection, CDI, and others.**Fig. 5** Schematic of string-wound sediment cartridge filter. Suspended solids from untreated water will accumulate throughout the depth of the filter material, while dissolved contaminants are not retained. Therefore, the classification and removal efficacy of sediment filters is highly dependent on the pore size of the filter media (reprinted with permissions from^{54,57}; Copyright© Filters Fast LLC, 2020; Copyright© UNISUN, 2020).

Table 6. Comparison of five types of ion exchange resins^{59,190}.

Type	Framework charge	Functional groups	Targeted pollutant ions	Suitable pH	Application
SAC resin	Negative	-SO ₃ H	Ca ²⁺ , Mg ²⁺	Whole range	Water softening, demineralization
WAC resin	Negative	-COOH, -CHPO(OH)	Ca ²⁺ , Mg ²⁺ , H ⁺	5–14	Demineralization and de-alkalization
SBA resin	Positive	-NR ₃ ⁺	SO ₄ ²⁻ , NO ₃ ⁻ , Cl ⁻ , HCO ₃ ⁻ , total organic carbon (TOC)	Whole range	Demineralization, de-alkalization and desilication
WBA resin	Positive	-NH ₂ , -NHR, -NR ₂	C ₆ H ₅ O ₃ ³⁻ , SO ₄ ²⁻ , C ₄ H ₆ O ₆ ²⁻ , PO ₄ ³⁻ , NO ₂ ⁻ , Cl ⁻ , CH ₃ COO ⁻ ,	1–9	Organic acids and common anions
MSC resin	Negative	Amino-carboxylic groups	Metal ions such as Co ²⁺ and Pb ²⁺	Based on metal type	Removal of metal ions in dilute solution

groups based on their framework (Table 6): strong-acid cation (SAC) resins, weak-acid cation (WAC) resins, strong-base anion (SBA) resins, weak-base anion (WBA) resins, and metal-selective chelating (MSC) resins⁵⁹. Cation resins are extensively used in the water softening process, removing hardness ions (e.g., Ca²⁺, Mg²⁺, and other divalent cations). WAC resins are more effective for treating feed waters containing a high concentration of hydrogen peroxide or chlorine than SAC resin because they have a higher resistance to corrosive oxidants and are more stable. It is worth noting that different anion resins have a varied affinity to different acids, and WBA resins cannot remove weak acids such as carbon dioxide and silica⁶⁰.

For POU applications, IEX resins meet the needs of water softening and demineralization. An acidic environment with high lead concentration might occur when solders and/or pipes corrode⁶¹. Cation softening resin is used to adsorb positively charged lead and many other metal ions. With a high molecular weight and a 2⁺ valence, lead has a high affinity towards the cation resin, MSC resin⁶². In addition, perchlorate can be removed to a very low level by SBA resin⁶³. The major concerns for POU versions of the IEX resin involve its regeneration process. Even under strong acids, lead-laden cation resin cannot fully strip lead from the resin⁶¹. Similarly, perchlorate attaches strongly to the anion resin. The safe and economical disposal of high-concentration regenerant brines is also an environmental concern.

Activated carbon. Activated carbon (AC) is the most commonly employed commercial POU filter in the United States⁶⁴. AC is created from charcoal by treating it with extremely hot gases, leaving pure carbon with many microscopic pores. Granular activated carbon (GAC) is a ubiquitous form of AC water filters in residential water filter systems. The carbon particles repel water and strongly attract nonpolar organic compounds via intermolecular Van der Waal's and hydrophobic interactions. Van der Waal's interactions are almost universally attractive and based on permanent, temporary, and induced dipole interactions between the atoms of the GAC and chemical compounds; hydrophobic attraction occurs between nonpolar compounds or nonpolar moieties within complex molecules. Highly polar and charged compounds can experience electrostatic and hydrophilic repulsion, which makes them less likely to be well removed by GAC. The surface area available for adsorption is extremely large due to the large quantity of micropores in the carbon. GAC is thus used to remove organic contaminants, some heavy metals⁶⁵, and DBPs such as trihalomethanes (THMs).

In addition to bare GAC, several surface modification methods have been researched to enhance the affinity to different impurities, including chemical treatment, impregnation, and plasma treatment⁶⁶ (Fig. S3). AC can be chemically modified to have an acidic or basic surface. In most cases, an acidic surface has typical functional groups of carboxylic acid, lactone, phenol, or lactol groups, while a basic surface is represented by the existence of chromene, ketone, pyrone, and nitrogen groups⁶⁷. AC can also be impregnated with metals and metal oxides. These additive crystallites will disperse in carbon pores and become active sites for contaminant adsorption⁶⁶. Silver-impregnated activated carbon (SIAC) is one promising POU filter medium based on this removal mechanism. Another class of surface modification is plasma treatment. Under vacuum or atmospheric conditions, AC is treated with air or oxygen plasma to create oxygen functional groups, which makes AC more active⁶⁶.

The novel SIAC has extensive use in POU water treatment. This filter type has high removal efficiency towards the natural organic matter (NOM), disinfection byproducts (DBPs), trihalomethanes (THMs), and many other key drinking water contaminants. Rajaeian et al. discussed the silver leaching mechanism of SIAC (Fig. S4). Their research reported that if the solution pH is properly controlled, additional bromide removal

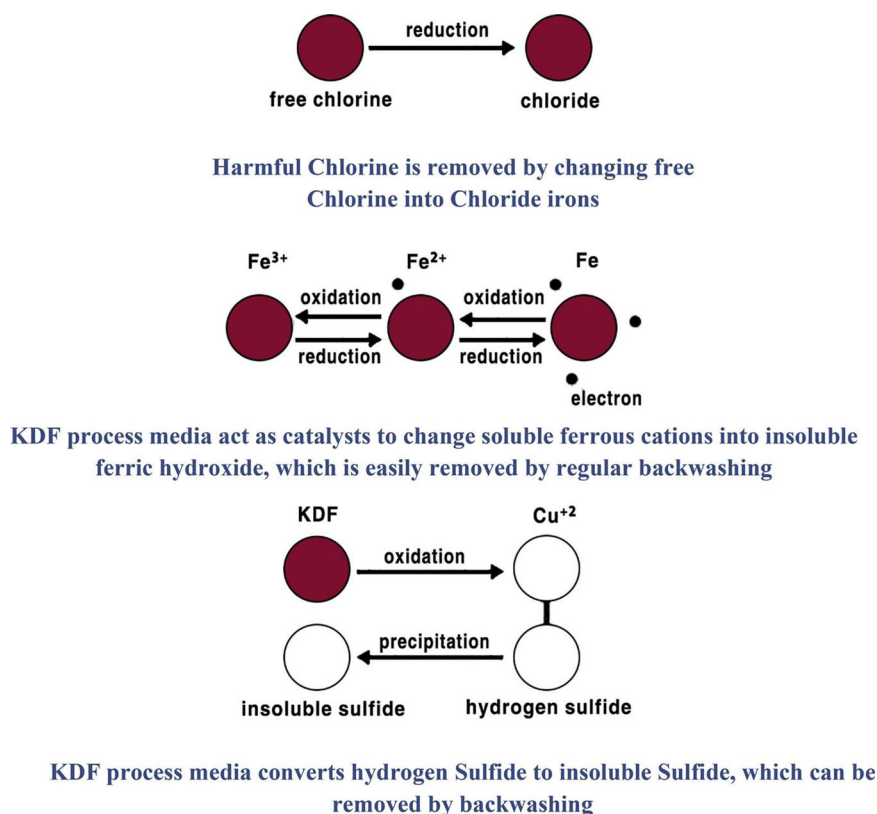


Fig. 6 Removal mechanism of KDF for chlorine, heavy metals, and hydrogen sulfide. Heavy metals dissolved in the water are reduced into an insoluble form and thus precipitate out so they can be retained in the filter medium (reprinted with permission from¹⁸⁰; Copyright © Elsevier, 2019).

can be achieved, while minimizing silver leaching⁶⁸. With preconditioning at pH 10.4, the release of silver is only 3%, which makes SIAC more competitive with longer service life⁶⁸. Watson et al. found that combined with an enhanced coagulation pre-treatment, SIAC (0.1% Ag) can reduce tTHMs by over 98%, bromide by $95 \pm 4\%$, and total dihaloacetonitriles (tDHANs) by $97 \pm 3\%$ (tDHANs = sum of dichloroacetonitrile (DCAN), bromochloroacetonitrile (BCAN), and dibromoacetonitrile (DBAN) concentrations)⁶⁹. The enhanced removal rate for Cr^{6+} has also been studied, over 94% Cr^{6+} removal by SIAC can be achieved by cost-effective H_2SO_4 pre-treatment⁷⁰.

KDF redox media. Kinetic degradation fluxion (KDF), a type of copper-zinc filtration, relies on the redox potential between these two metals to remove certain contaminants. Figure 6 diagrams the removal mechanism of KDF for various contaminants. Heavy metals dissolved in the water are reduced into an insoluble form and thus precipitate out so they can be retained in the filter medium⁷¹. KDF filters also reduce free chlorine and inhibit bacterial growth. Experiments showed that the oxidation-reduction potential (ORP) rapidly drops from 200 mV to -500 mV when feedwater passes through KDF⁷². This sharp decrease makes the environment unsuitable for bacteria to survive. However, KDF filters do not remove organic contaminants. For this reason, KDF is often used as a prefilter or combined stage with GAC (Fig. S5⁷³).

There are two primary types of KDF filters in the market for POU applications: KDF55 and KDF85 (see Table 7 for a comparison). Based on their differing composition, KDF55 is more suitable for chlorine, heavy metal, and bacteria removal, while KDF85 is a better choice for eliminating iron and hydrogen sulfide⁷⁴. A higher portion of zinc in the material enhances the reduction ability of KDF55. Thus, it is more effective for free

chlorine removal. However, in large-scale applications, maintaining high performance of the KDF filter requires a backwashing procedure with a high flow rate, about 30 gallons per minute per square foot of bed surface area⁷⁵. The backwash rate is also supposed to be tunable to the environment temperature. Fouling problems and poor efficacy might result if backwashing procedures are not properly followed. Innovative modification of KDF process media is thus expected to improve the filter. Nano-KDF is a pioneering nano-sized filter medium which originated from KDF^{76,77}. Its specific surface area is over 100 times larger than the conventional type. Even under high initial chlorine concentration of 3 mg/L, the removal efficiency can be over 99.9%⁷⁷.

Novel green filter media. In residential water filtration systems, cheaper and greener alternatives are often preferred by consumers. Many companies have developed such eco-friendly water filters in recent years. By using recyclable raw materials, the carbon footprint and manufacturing cost is greatly reduced. For example, Glanris (<https://www.glanris.com>) is a 100% green product made from rice hulls, reducing 98% of carbon emissions during the manufacturing process; hence, the "green" aspect of their filter media⁷⁸. The biodegradable raw material makes it non-toxic and easy to dispose. At the same time, the widespread availability of its raw material lowers the price to \$3–6 per lb for specialty metal removal and \$3–10 per lb for nutritional/vitamin grade. By combining features of both GAC and IEX resins, this hybrid technology achieves in a single step removal of a wide range of organics and heavy metals⁷⁹. High chlorine removal capacity is developed with fast kinetics and color in drinking water can be eliminated as well. Another example is Swift Green Filters (<https://swiftgreenfilters.com>) who makes AC from renewable coconut shells, which has the advantage of 50% more micropores

Table 7. Comparison of KDF55 and KDF85^{71,75}.

Type	Formulation	Particle size (mm)	Density (g/cm ³)	Removal rate for contaminants		
				Chlorine	Iron	Hydrogen sulfide
KDF55	50% copper and 50% zinc	0.145–2	2.4–2.9	>99%	>98%	na
KDF85	85% copper and 15% zinc	0.149–2	2.2–2.7	na	>90%	>95%

na not available.

Table 8. Comparison of MF, UF, NF, and RO membranes^{84,191}.

	Particle size (μm)	Pressure (bar)	Removal efficiency Bacteria	Protozoan	Viruses	NaCl
MF	0.1–1	0.5–1	na	log 2–5	log <1	/
UF	0.01–0.1	1–10	na	log >6	log >3	/
NF	0.001–0.01	5–70	log 3–6	log >6	log 3–5	10–50%
RO	0.0001–0.001	10–100	log 4–7	log >7	log 4–7	90–99%

Note: log refers to log removal value (LRV), where log 2 is 99%, log 3 is 99.9%, etc.
na not available.

than other plant-based shells⁸⁰. Since the global consumption of coconuts has rapidly increased in recent years, the massive amount of coconut husk waste can be sustainably reused, providing a steady and environmentally friendly raw material source for the company. Key water impurities like turbidity, lead, mercury, chlorine (taste and odor), and asbestos can all be effectively reduced⁸¹. Swift's green water filters are categorized into refrigerator filters, under the sink systems, tap filters, alkaline water filters, etc.

Membrane filtration

Compared with media filtration, membrane filters require no chemical additives to achieve a target separation, and act as absolute barriers⁸². Pressure-driven membranes are divided into 4 categories⁸³ (Fig. S7): microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO)⁸⁴. Most of MF/UF membrane products are made of commodity polymers such as polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), polyethylene (PE), polypropylene (PP), polysulfone (PSU), and polyethersulfone (PES), although ceramic analogs are also widely available^{85,86}. Both NF and ROMs are most often composite (multi-layered) structures where a denser film coats over a MF/UF-type membrane to provide enhanced selectivity towards dissolved substances. Depending on the pore size, membranes have distinct target pollutants and removal efficiencies (Table 8).

Among the four types, RO is the most popular membrane type in POU systems. Unlike MF, UF, and NF membranes, RO membranes are the “tightest,” allowing water to pass, but virtually everything else in water is retained down to simple salts (e.g., NaCl) and small organic molecules >100 Da⁸⁷. It is thus highly efficient in rejecting dissolved organic and inorganic contaminants (Table 9). Even for pollutants with low molecular weight, only trace concentrations exist after RO filtration, and the values are typically below health limits⁸⁸. ROMs also completely reject pathogens, with no *E. coli* or viruses detectable in RO permeate⁸⁹. Moreover, with the feedwater concentration ranging from 0.5 to 1500 mg/L, over 99% of PFOS can be rejected by ROMs⁹⁰. However, ROMs may not be as effective for carcinogenic nitrogen DBPs, as only 50–65% or less

Table 9. Rejection rates of various pollutants by RO membranes^{191,192}.

	Pollutant	Rejection rate
Conventional contaminants	Sulfate	99.7–99.98%
	Phosphate	99.7–99.99%
	BOD	98%
	COD	96%
	TOC	>96%
Emerging contaminants	EDCs	95–99%
	PFOS	>99%
	NDMA	50–65% or less; 59–75% with UV
	1,4-dioxane	96% with GAC

NDMA may be removed by RO⁹¹. Currently, UV treatment is an effective method for removal of NDMA. NDMA in aqueous solutions undergoes direct photolysis upon UV exposure, which further leads to dimethylamine, and nitrite and nitrate ions as the major degradation products⁹². A combination of RO and UV disinfection is thus preferred to improve efficiency to 59–75%⁹¹. The previously mentioned emerging carcinogen 1,4-dioxane can also be reduced by nearly 96% by a removal system combining RO and GAC⁹³.

While ROMs are common in POU water filters, they are more expensive than GAC and sediment filters. Many consumers find less expensive filters sufficient for their needs. However, RO units produce purer water than other commercially available technologies. Also, pre-treatment is necessary during this process; otherwise, membrane fouling or damage can quickly occur. Given sufficient pressure, nearly all dissolved solutes can theoretically be removed, but realistic removal rates on the order of 90–99% are possible for contaminants that cannot be removed by other filtration methods. RO systems are thus in demand among those with a high standard for water quality. Some water filter companies address differing customer standards by selling versions of systems that differ only in the inclusion of a ROM.

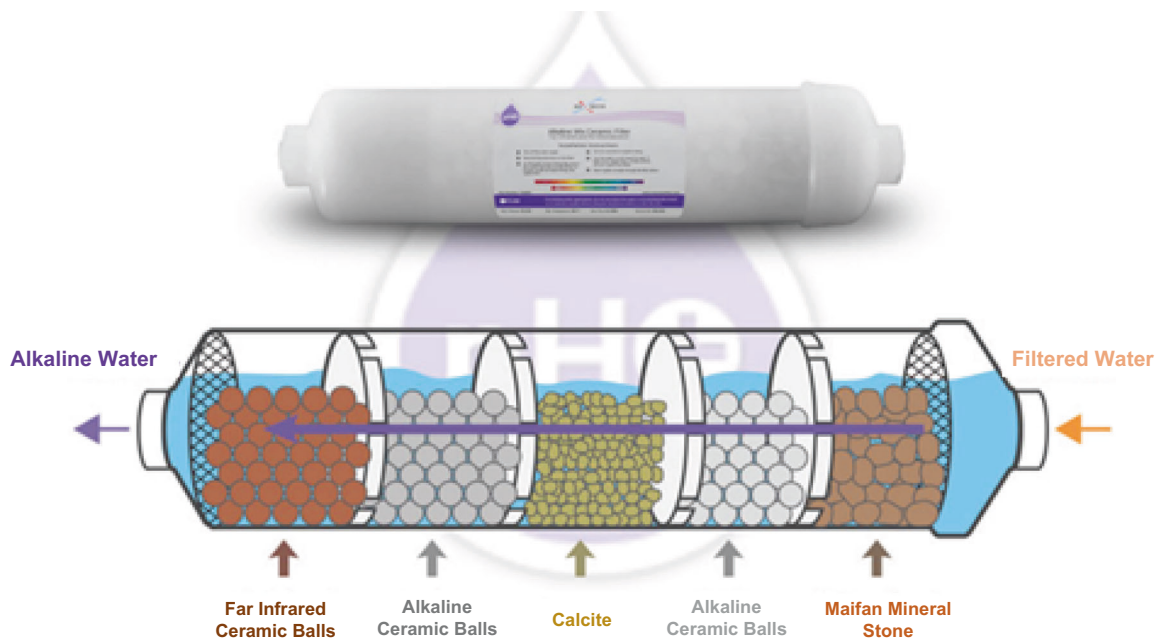


Fig. 7 Schematic of 5-in-1 remineralization filter. Remineralization aims to adjust the alkalinity of RO-filtered water by re-introducing healthy minerals; tap water RO permeate is deficient in healthy minerals, has a slightly dry, burning feeling to the tongue, and is slightly corrosive with $\text{pH} < 6.0$ (reprinted with permission from¹⁰⁸; Copyright © EZFILTER, 2020).

UV disinfection

UV irradiation has been increasingly used in water disinfection to inactivate microorganisms because it adds no chemicals, does not produce harmful DBPs, and does not cause disinfectant resistance in bacteria⁹⁴. The radiation penetrates the microorganisms and results in photochemical damage by impairing nucleic acids (DNA or RNA). Such damage further disables microorganisms from replication and infection. In this way, microorganisms are rendered unable to function or reproduce and might even be killed^{95,96}.

Mercury-based lamps are often used as the UV emission source for the disinfection system. After the excitation of mercury vapors in the lamp, UV rays are generated. UV mercury lamps are mainly categorized into two types: low pressure and medium pressure. With pressure under 10 torr, the emission of conventional low-pressure mercury lamps is monochromatic at 254 nm⁹⁷; often used at low flow rates where the exposure time to UV can be longer. Medium pressure (approximately 1000 torr) UV lamps have higher emission intensity and cover a broader range of wavelengths (200–400 nm)⁹⁷. Because of the high energy demand for emission, medium-pressure UV lamps are exclusively used in more commercial or regulatory contexts such as drinking water or wastewater treatment plants.

UV-LED has emerged as a viable alternative over the past decade to achieve a more sustainable, low-energy UV disinfection (Fig. S6)^{94,98}. Its small size (5–9 mm diameter) enables easy transport and disposal in POU application⁹⁹. As LED does not need warm-up time, it saves energy and allows intermittent use, thus leading to lower system cost. The germicidal efficiency of UV-LEDs is reported to be at least as good as low-pressure UV disinfection lamps¹⁰⁰. In most cases, the germicidal effect of UV-LEDs is enhanced compared to conventional UV mercury lamps as they can incorporate an LED array of differing UV wavelengths. UV radiation with different wavelengths have varied microorganism inactivation efficiencies¹⁰¹; thus, UV-LED can maximize its combined germicidal effect. Pulsed irradiation by UV-LEDs can also be used to improve germicidal effects¹⁰². At 272 nm under pulsed UVC, the log inactivation rate for *E. coli* is 3.8 higher than continuous illumination with the same UV dose¹⁰³.

Remineralizing media filters

Remineralization aims to adjust the alkalinity of RO-filtered water by re-introducing healthy minerals; tap water RO permeate is deficient in healthy minerals, has a slightly dry, burning feeling to the tongue, and is slightly corrosive with $\text{pH} < 6.0$ ¹⁰⁴. Product water after remineralization not only makes RO-treated water more palatable, but also non-corrosive¹⁰⁵, fulfilling the following water quality criteria: pH between 6.5 and 8.5; alkalinity $> 80 \text{ mg/L}$ as CaCO_3 , and calcium carbonate precipitation potential (CCPP) range of $80 < \text{CCPP} < 120 \text{ mg/L}$ as CaCO_3 ^{106,107}.

Figure 7 gives an example of a 5-in-1 alkaline, remineralization, and far-infrared filter¹⁰⁸. There is a bit of marketing mythology surrounding some remineralization filters with statements such as “Like the flow of a mountain spring, water passes through mineral rocks in sequence.” For other media, such as the Maifan Mineral stone (a.k.a., “Japanese & Chinese Medicine Stone”), product claims include “releasing beneficial microelements, stabilizing water pH, and absorbing chlorine and heavy metals, Maifan stone is widely used in traditional Chinese treatments of many conditions like digestive problems and high blood pressure”⁸⁴. The “alkaline ceramic ball” claims a “capacity to break down a big water molecule groups into smaller ones” and to “activate water”¹⁰⁰. Another claim is that ceramics can generate far-infrared rays (FIR), and hence, the alkaline ceramic ball offers enhanced filter performance in antibacterial, activation, absorption, and water purification¹⁰⁰. We find no scientific evidence supporting any of the above claims and assume they are largely marketing stories; however, such 5-in-1 remineralizing filters appear popular following ROMs in high-end POU filtration systems.

Emerging technologies: an example of CDI

Apart from the above technologies, a growing number of novel water treatment technologies have emerged to meet the increasing removal needs for emerging contaminants and from higher regulatory requirements. Water treatment based on electrochemical principles is one promising technology, which is presently emerging. Electrochemical water treatment technologies

include electro-oxidation, electro-reduction, electro-coagulation, electro-flotation, electro-decantation, capacitive deionization (CDI), and others¹⁰⁹. In this section, CDI is chosen as an exemplar electrochemical water treatment technology. Its working principles, developing history, and comparison between different types are discussed.

CDI, and its various derivatives, are promising POU water treatment technologies that use applied electric fields to separate dissolved ions by various mechanisms. Ions in feed water can be immobilized to two paired porous electrodes by applying a low-voltage electric field between the electrodes¹¹⁰. This process generally follows electric double layer theory where the charge on the electrode surfaces (from the applied potential) is neutralized by the accumulation of counterions from solution¹¹¹. Positively charged ions such as Ca^{2+} , Mg^{2+} , and Na^{+} will be adsorbed to the negative cathode, while negatively charged ions such as Cl^{-} and SO_4^{2-} will be adsorbed to the positive anode. The electrodes are regenerated (e.g., ions released) by reversing the applied potential releasing electrosorbed ions.

After years of research and development, different architectures of the CDI module have been developed with various advantages and disadvantages (Table 10). Flow between electrodes is the most conventional format of CDI designed by Blair and Murphy in 1960¹¹². The desalination efficiency of CDI was improved through an innovation by Johnson et al.¹¹³ by pumping feed water through the porous electrodes rather than between the solid electrodes. Researchers are devoted to combining CDI with existing filtration technologies such as membranes^{114,115} or modifying the surface and material for the electrodes^{116–118}. However, high manufacturing cost limits widespread deployment of CDI-based POU water treatment products.

More recently, a form of CDI called “capacitive coagulation” has emerged as an electrically driven alternative to chemical coagulation with the advantages of no chemical use, no sludge production, and higher energy-efficiency than conventional chemical adsorption (<https://electramet.com>). A wide range of heavy metals like lead, copper, manganese, iron, zinc, nickel, and cobalt have been removed with over 99% selectivity¹¹⁹.

Summary of POU technology efficacy

A summary of available peer-reviewed studies on POU water treatment technologies is provided in Table 11, where we compare contaminant types, specific contaminants, treatment technologies, and removal rates. The reported removals for nearly all of the technologies are over 90% and, in many cases, >99%. It is fair to assume that the reported removals can be expected from the technologies as tested and reported. What is not known from peer-reviewed studies and from for-profit companies’ product performance claims, is how long a given technology maintains the reported level of performance in terms of time, volumetric throughput, or contaminant mass loading. This is difficult to evaluate due to the lack of data from published scientific studies or company claims.

COMMERCIALY AVAILABLE POU SYSTEMS

Here we consider the filtration and purification components most commonly employed, in what formats (e.g., under the sink, countertop, etc.), and how they are combined to create various POU water filtration systems. Mass-produced water filters need to be effective at removing contaminants, and also, must be compact, low-cost, and easy to maintain. These constraints place some limits on the purification technologies that consumers can access, which drives most consumer products to use highly commoditized filter media. We compiled data from 11 POU water filter companies’ websites, and the configurations of their systems are summarized below. Individual filters and system components

Table 10. Common types of CDI developed for desalination.

CDI type	First demonstration	Structure characteristics	Advantages	Disadvantages
Flow between electrodes	Blair and Murphy (1960) ¹¹²	Very simple structure (no membranes or flow-electrodes)	Reduced fouling potential; low system cost	Most conventional; low efficiency and selectivity
Flow-through electrodes	Johnson et al. (1970) ¹¹³	Compact system with feed water pumping through the porous electrodes	Faster desalination with lower resistance; minimization of the separator thickness	High pressure requirement
Membrane CDI	Lee et al. (2006) ¹¹⁴	Ion exchange membranes on the separator-side of each electrode (CEM at the cathode, AEM at the anode)	Improved charge efficiency; enhanced tunability to selectively remove ions	Extra membrane cost
Inverted CDI	Gao et al. (2015) ¹¹⁶	Chemically modified surface of the carbon xerogel anode; inverted behavior: ion desorption during cell charging, and ion adsorption during cell discharging	Longer service life by protecting the carbon electrodes from oxidation; enhanced salt removal; improved system stability	Limited overall salt capacity of the cell due to the small working voltage window
Hybrid CDI	Lee et al. (2014) ¹¹⁵	An asymmetric system that includes: a sodium manganese oxide (NMO) electrode (cathode), an anion exchange membrane, and a porous carbon electrode (anode)	Excellent stability; high ion removal rate; suitable for a highly concentrated feed water	Higher manufacturing requirement; higher cost
Desalination battery	Pasta et al. (2012) ¹¹⁷	Combination of a battery electrode (ions captured by chemical bonds) and a capacitive electrode	High desalination capacity; ion selectivity	Low performance rate of desalination
FCDI: flow-electrode capacitive deionization	Jeon et al. (2013) ¹¹⁸	Suspended carbon material	Ability to desalt feed water with high salt concentration; does not require discharging; easy to scale up by increasing the number of flow-electrodes used.	High cost

Table 11. Removal efficacies summary of POU technologies.

Contaminant type	Contaminant	Removal method	Removal efficacy	References
Disinfection byproducts	Bromate	An enhanced coagulation pre-treatment with a silver-impregnated activated carbon (SIAC)	95 ± 4%	Watson et al., 2016 ⁶⁹
	Chlorite	Regenerated granular activated carbon (GAC)	>99%	Sabrina and Carlo, 2004 ¹⁹³
	Haloacetic acids	Multi-stage reverse osmosis (RO)	>75%	Wang et al., 2018 ¹⁹⁴
	Total trihalomethanes	An enhanced coagulation pre-treatment with a SIAC	> 98%	Watson et al., 2016 ⁶⁹
Disinfectants	Chloramines	An ultrafiltration system combining sediment and carbon prefilters	95%	Woodard, 2020 ¹⁹⁵
	Chlorine	KDF	>99.9%	Zhai et al., 2010 ⁷⁷
Trace element	Arsenic	RO membrane	>99%	Chen et al., 2020 ¹⁹⁶
	Lead	Weak-acid cation exchange resin Lewatit CNP 80	98–99%	Erol and Turkan, 2007 ¹⁹⁷
	Copper	RO membrane with a chelating agent Na ₂ EDTA	99.5%	Mohsen-Nia et al., 2007 ¹⁹⁸
	Iron	Cation exchange resin Lewatit TP-207	>90%	Korngold, 1994 ¹⁹⁹
	Zinc	Weak-acid cation exchange resin Lewatit CNP 80	98–99%	Erol and Turkan, 2007 ¹⁹⁷
	Nickel	RO membrane with a chelating agent Na ₂ EDTA	99.5%	Mohsen-Nia et al., 2007 ¹⁹⁸
	Chromium (VI)	H ₂ SO ₄ pre-treatment with a SIAC	94%	Mishra et al., 2019 ⁷⁰
	Uranium	RO	95–98%	Khedr, 2013 ²⁰⁰
	Nitrate	Continuous electro-coagulation unit with vertical monopolar electrodes	96%	Majlesi et al., 2016 ²⁰¹
	NDMA	UV disinfection treatment	>90%	Sgroi et al., 2018 ²⁰²
Nutrient	PFOS	RO membrane	>99%	Tang et al., 2006 ⁹⁰
	PFOA	Anion exchange resin	>99%	Yao et al., 2014 ²⁰³
Organic compound	1,4-dioxane	A removal system combining RO and GAC	Nearly 96%	Home Master, 2017 ⁹³
	MTBE	UV/H ₂ O ₂	98%	Levchuk et al., 2014 ²⁰⁴
	Dieldrin	Bromopropyl functionalized silica nanofibers	91.02%	Yue et al., 2012 ²⁰⁵
	Diazinon	Nano-titania modified activated carbon	95%	Hassan et al., 2017 ²⁰⁶
	Atrazine	Activated carbon/iron oxide composites	94%	Castro et al., 2009 ²⁰⁷
	Alachlor	Pd catalyst supported on activated carbon	97.5%	Calvo et al., 2008 ²⁰⁸
	Natural organic matters (NOM)	Carbon black adsorption and alum coagulation	Almost 90%	Wang et al., 2010 ²⁰⁹
	Sulfate	RO membrane	99.7–99.98%	Bellona et al., 2004 ²¹⁰
	Phosphate	RO membrane	99.7–99.99%	Bellona et al., 2004 ²¹⁰
	Fluoride	RO membrane	>96%	Dolar et al., 2011 ²¹¹

are listed in order when they could be determined. Price ranges are listed where available; the range of products were selected to reflect the lowest and highest priced products within the category. The prices shown were listed on the companies' websites, including discounts, as of December 2020. Many available products were not included in this analysis as the one's shown are simply indicative of industry norms.

Under-the-sink water filters

One of the most popular POU locations is under the kitchen sink, for filtering water just before it comes out of the tap. Most households with these systems use untreated tap water for most of their water needs (such as showers and washing machines) and a small amount of filtered water for drinking and cooking. Under-the-sink filters are designed to purify only a few hundred gallons

of water before needing replacement of filter media. They may be further divided based on the number of filtering stages or the presence of a ROM. There is considerable flexibility in the number of stages depending on the needs of customers, but may comprise up to seven stages including a sediment prefilter (SED), ion exchange (IEX), KDF or GAC media filters, activated carbon block (ACB) filters, RO membrane (ROM), remineralization media filters (ALK), UV sterilization (UVS) and/or postfiltration activated carbon (PAC) (Fig. 8).

Table 12 summarizes the abundance of under-the-sink water filter media across several brands. Among the units including an ROM, APEC Water offers the most models. It has three five-stage models with sediment, two carbon blocks, RO, and GAC postfilter (\$190–280), two models with added remineralization (\$230–320), two models with added UV before postfilter (\$280–290), one model with added UV and remineralization (\$310), two models



Fig. 8 Under-the-sink RO filtration. There is considerable flexibility in the number of stages depending on the needs of customers, which may contain up to seven stages including a sediment prefilter (SED), ion exchange (IEX), KDF or GAC media filters, activated carbon block (ACB) filters, RO membrane (ROM), remineralization media filters (ALK), UV sterilization (UVS) and/or postfiltration activated carbon (PAC) (reprinted with permission from¹⁸¹; Copyright© Express Water Inc., 2020).

with added pumps for low-pressure households (\$370–400), and one compact four-stage model with sediment, GAC, RO, and GAC (\$250)¹²⁰. Similarly, Aquasana has one model with four stages: sediment, AC, RO, and “Claryum”, which is a special design consisting of AC, sediment, and IEX (\$200)¹²¹. Culligan has one tankless model with RO only¹²² and two models with storage tank and four stages: sediment, AC, RO, and specialized carbon block^{123,124}. Whirlpool has three models with three stages and a tank: sediment/AC combined prefilter, RO, and AC postfilter^{125,126}. Pelican has one six-stage model with 20 μ m SED, GAC prefilter, RO, two GAC postfilters, and calcite remineralization (\$220)^{127,128}. GE and Kinetico provide comparatively limited choices, with one model for each brand. The former brand provides a model with GAC pre- and postfilters and tank (\$180)^{129,130}, while the latter has four stages: prefilter, RO, storage tank, and AC postfilter.

There are also many under-the-sink water filters without an ROM. For example, Aquasana has two models with SED and two “Claryum” stages (\$142–175) and one model with two Claryum stages (\$99)^{131,132}. GE has one parallel-flow dual GAC model (\$130)¹³³ and two single-stage GAC filters (\$70–80)^{134,135}. Products from iSpring are more complicated. This brand provides one four-stage system with sediment, UF membrane, hybrid KDF/GAC, and carbon postfilter (\$170)¹³⁶; one similar compact model, but with UF as the final filter (\$130)¹³⁶; one three-stage model with sediment and two AC blocks (\$120)¹³⁶; and one two-stage system with GAC and AC block (\$194)¹³⁷. Similarly, Pelican has one single-stage GAC (\$74)¹³⁸ and one three-stage system with SED and two catalytic GAC filters (\$154)¹³⁹. Finally, Whirlpool has one model with two AC stages (the first might have a combined sediment stage)¹⁴⁰, one three-stage system designed for microbiological

Table 12. Number of products using each treatment type in under-the-sink systems.

		SED	KDF	GAC/ACB	RO	UV	ALK	Other	Total	Price
Systems w/RO	APEC	11	0	11	11	3	3	0	11	\$190–400
	Aquasana	1	0	1	1	0	0	1	1	\$200
	Culligan	2	0	2	3	0	0	0	3	na
	iSpring	10	0	10	10	2	4	1	10	na
	Kinetico	1	0	1	1	0	1	0	1	\$180
	Pelican	1	0	1	1	0	1	0	1	\$220
	Whirlpool	3	0	3	3	0	0	0	3	na
Systems w/out RO	Aquasana	3	0	3	N/A	0	0	3	3	\$99–175
	GE	0	0	3	N/A	0	0	0	3	\$70–130
	iSpring	3	2	4	N/A	0	0	2	4	\$120–175
	Kinetico				N/A				2	na
	Pelican	1	0	2	N/A	0	0	0	2	\$74–154
	Whirlpool	0	0	3	N/A	0	0	0	3	\$90

N/A not available.

purification containing AC, and one single-stage AC system designed for kitchen and bath use (\$90)¹⁴¹.

Countertop and pitcher water filters

Table 13 summarizes configuration details of available countertop and pitcher water filters. Countertop systems, among the cheapest of home water filters, often include only one or two stages which may combine multiple filter media (e.g., sediment and GAC). Some are pressurized and are essentially compact versions of under-the-sink systems. However, many are not pressurized: tap water is poured in and gravity alone moves the water through a small filter. Gravity-only filters are very popular and sold in retail hardware, grocery, and mega-stores; water filtration can be slow and most are designed to improve water taste (with some health protection benefits) removing residual chlorine, dissolved organics, and some metals like lead and copper. For some pitcher filters, the filtration process takes only around 30 s. Customers can simply pour water into the pitcher, then get clean drinking water in the pitcher reservoir as feedwater passing through the filter cartridge. In addition, the price of a common water filter pitcher is relatively lower than other filter types, typically less than \$40. However, since most pitcher filters only contain GAC, IEX, and/or KDF media, not all contaminants are removed, especially some heavy metals, volatile organic compounds, and hormones.

Refrigerator water filters

Many refrigerators are designed to deliver filtered cold water and ice. All water that passes through a refrigerator is filtered first using a replaceable filter cartridge. This cartridge may be any combination of GAC/ACB, WAC, SBA, KDF, and/or media, but most often is solely some form of GAC or ACB. For example, GE¹⁴² and Whirlpool¹⁴³ have numerous GAC/ACB models for refrigerators, while iSpring has one single-stage GAC (\$39) model (Fig. S8)^{144–148} and one two-stage model with GAC and remineralization (\$40)¹⁴⁹.

Faucet-mounted water filters

By design, faucet head filters are among the smallest filters available. They usually consist of a single stage with a granular filter medium, which may consist of a couple components mixed in one housing (e.g., KDF and GAC). For example, Brita has two POU models with sediment filter and carbon block filter (\$19–30) and PUR has four models with slightly more expensive prices

(\$20–35)¹⁵⁰. iSpring has two models with what appears to be KDF, GAC, and calcium sulfite remineralization according to a picture on their website (\$29–35) (Fig. S8)¹⁴⁷.

Showerhead water filters

These filters are designed to filter shower water, so drinking water purity is not strictly required; however, many volatile organics could be inhaled while showering and other contaminants could be taken up by dermal absorption from showering or bathing. Many shower filters are designed to remove chlorine (which dries out some people's skin) and may include one or more remineralization stages for adding minerals deemed to be beneficial to the skin. Both GE and Pelican only have one model for showerhead water filters. The model from GE is similar to a KDF filter (\$23)¹⁵¹, while Pelican's model is more complex with copper-zinc, GAC, and remineralization media (\$42)¹⁵². Aquasana has three two-stage models which are KDF followed by AC (\$55–65)^{49,51}. Models from iSpring are even more complicated (Fig. S8), with three models of 15 stages each. In order, the stages are sand, stainless-steel mesh, particulate, many remineralization and ion exchange stages, KDF, GAC, particulate, stainless-steel mesh, and finally sand (\$19–26).

SMART POU WATER FILTERS

Definition of “Smart Water Filter”

One definition of “smart” originates from computer science, where SMART is a fault detection and monitoring system short for Self-Monitoring, Analysis and Reporting Technology¹⁵³. The expectation about “smart” is higher now with the expansion of Internet coverage and WiFi technology. Nonliving things are becoming animate and “smart” through artificial intelligence (AI) and machine learning (ML) by interacting with human beings. Therefore, the present study proposes a new, expanded definition for “smart” with the following equation: Self-Monitoring, Analysis, and Reporting + Interaction with Human through Internet = SMART. In recent years, “smart” is an increasingly attractive product description for home equipment and appliances, including water filters. According to Investopedia.com¹⁴, “smart home” refers to a convenient home setup where appliances and devices can be automatically controlled remotely from anywhere with an Internet connection using a mobile or other networked device. Devices in a smart home are interconnected through the

Table 13. Product summary of filter media in countertop and pitcher systems.

Brands	Filter type	Model configuration	price
APEC	Countertop	Sediment filter + GAC + RO + GAC	\$230
	Countertop	Sediment filter + GAC + RO + GAC + additional case	\$270
	Countertop	Sediment filter + GAC + RO + remineralization	\$250
	Countertop	Sediment filter + GAC + RO + remineralization + additional case	\$290
Aquasana	Countertop	Three models, all GAC (without pump) ²¹²	\$57
	Countertop	Three models, all GAC (with pump) ²¹³	\$130
PUR	Pitcher	Five pitcher models with tap ²¹⁴	\$17–40
Brita	Pitcher	Numerous pitcher models (more than ten, no clear count available) with integrated sediment filter, GAC, and ion exchange ^{215,216}	\$20–45
iSpring	Countertop	One single-stage carbon block ²¹⁷	\$41
	Countertop	One two-stage GAC and carbon block ²¹⁸	\$80
Kinetico	Countertop	One customizable model with five stages, storage tank, and tap: prefilter (sediment or carbon/sediment), two auxiliary filters (antimicrobial, volatile organic compounds, arsenic, perchlorate, chloramine, remineralization), RO between auxiliary filters, activated carbon postfilter ²¹⁹	–
Pelican	Countertop	One single-stage GAC model ²²⁰	–
	Countertop	One GAC model ²²¹	\$56

Internet, allowing the user to control functions such as home security systems, access to the home, temperature, lighting, music, and home theater equipment. Here are a few key takeaways about smart home technology.

- A smart home allows homeowners to control appliances, thermostats, lights, and other devices remotely using a smartphone or tablet through an Internet connection.
- Smart homes can be set up through wireless or hardwired systems.
- Smart home technology provides homeowners with convenience and cost savings.
- Security risks and bugs continue to plague makers and users of smart home technology.

Further, “smart products” include features such as context awareness through data collection, autonomous operation via AI/ML algorithms, and WiFi or Bluetooth connectivity and connection to other devices and/or the Internet¹⁵⁴. For example, one smart air filter can not only actively track the filter life, but also provide environmental air quality information and tips for the user through a convenient mobile app¹⁵⁵. Similar to a smart air filter, a smart water filter could allow the user to control the appliance remotely and keep track of important details such as filter lifespan and filtered-water quality. However, there is little consensus on what constitutes a smart water filter. Moreover, current smart water filters are not actually smart based on the fact that they can neither be remotely controlled nor provide necessary water quality information to the consumers.

Most “smart” water filter systems in the U.S. market only have a timer, flow counter, or “# of times used” counter to remind the user when to replace a filter. These rely on preset assumptions of filter usage and water quality, and do not directly measure the quality or quantity of water consumed. Water filter companies which use a battery-powered timed replacement feature include GE, Pelican, and Whirlpool. Kinetico claims to use a smart reminder, but its products simply use a flow counter to shut off the system when a prespecified number of gallons have been used¹⁵⁶. Flow sensors record the rotation of an impeller wheel as water moves through the device¹⁵⁷. Brita pitchers use a different method: a sensor in the lid counts how many times the lid has been opened to fill the pitcher, approximating the output of a flow sensor. Some sensors, such as those used in PUR faucets¹⁵⁸,

track both time and water flow. While more sophisticated than a time-based reminder, a flow-based reminder still does not use actual water quality information to assess filter performance or treated-water quality. Moreover, water quality can vary considerably between different households in different regions with different water quality and based on the age of premise plumbing. Pre-programmed filter change reminders have limited ability to adapt to local water quality or assess whether a system is functioning as designed.

It seems obvious to incorporate smart technology and elements into POU water filters, in particular, to reliably notify the user when to replace the filter. Conductivity, pH, and ORP sensors are widely available and some for less than \$10 (presumably even less when purchased in bulk). However, we find limited evidence of such technologies in any commercially available POU products. A filter’s ability to remove lead, arsenic, and other harmful contaminants may be well-advertised, but it is not clear for how long that performance persists in a given household installation. A time- or flow-based change reminder is consistent in that a manufacturer can expect attentive customers to buy a replacement at predictable time intervals. This increases the ability of the manufacturer to plan their production and finances. Many customers may never replace their filter cartridges due to inconvenience or switching to a different filter brand. Customers in this group would also be unlikely to benefit from a more intelligent reminder system.

It seems likely that most consumers who will eventually replace their filters would prefer to do so when their system wears out or breaks rather than at a predefined time interval. If a product is developed which includes this feature, perhaps including sensors more sophisticated than TDS (total dissolved solids) (conductivity), then these capabilities could prove attractive. Users could be warned that contaminants have reached unacceptably high levels at the filtration system’s output, providing a more compelling reason to replace one or more components. The availability of in-line TDS sensors which can be plugged into existing water supplies indicates that measurement capabilities are in demand^{159,160}. Given the trend towards an Internet of Things, a smart water filter with electronics which accurately measures water quality would be a fitting contribution to the idea of a smart home.

Sensors that could make water filters smarter

In a smart water filter, evaluation of various parameters using sensors is necessary to monitor water quality. Many sensors have been developed to measure physical qualities of water or the presence of chemical contaminants. These include sensors for electrical conductivity (EC)—a surrogate for TDS, ORP, pH, turbidity, ion-selective electrodes as well as emerging optical, fluorescent, and spectrophotometric devices. Adding these sensors to water filter systems could allow users to check the quality of their water without worrying about silent product expiry. Moreover, the widespread use of sensors could push manufacturers to improve removal efficacy and address more diverse contaminants. Moreover, even if sensors like those described below were to be deployed in POU water treatment systems, they would not be truly SMART until they communicate to the system owner directly through some smart device like an Internet connected phone, tablet, or PC.

TDS sensors. One of the most common sensors is an EC sensor, which requires only a pair of electrical contacts to measure the resistance of water by applying a small current. EC can be closely correlated with TDS because dissolved ions in water allow electricity to flow more freely between the contacts^{161,162}. For instance, there is a fairly robust conversion factor from EC to TDS for fresh water, namely $1 \text{ mS/cm EC} = 640 \text{ ppm TDS}$ ¹⁶³. However, this is a crude measurement because conductivity fails to account for the specific ionic composition of the water. The TDS sensor is small and cheap, with simple versions available for close to \$10¹⁶⁴. The least expensive sensors can measure TDS within 10% accuracy¹⁶⁴, while more expensive ones can achieve 1% accuracy or better¹⁶⁵. Multiple forms of the sensor are available; Fig. S9^{160,166} depicts one sensor with exposed metal contacts and one in-line sensor which covers the contacts in a way that allows them to be placed in series with a water supply¹⁵⁹. Due to their simplicity and adaptability, TDS sensors are one of the most common devices for measuring water quality. HM Digital™ TDS Meter can achieve EC-to-TDS conversion easily, and some meters can even have selectable conversion factors. The Dual Inline TDS Meter is different from the first one as it can measure two different water lines together. As a result, customers can get TDS information about both tap water and filtered water at the same time.

Uncharged contaminants such as soluble hydrocarbons, DBPs, and some pharmaceuticals and pesticides cannot be detected by conductivity sensors because they do not change the ability of water to conduct electrical current. Some charged contaminants such as lead, chromium (VI), and arsenic—while they can be ionic—are toxic at levels in the parts-per-billion range, too small to be detected by all but the most precise conductivity sensors¹⁶⁷. Despite limitations, an EC/TDS sensor's measurements could be used to evaluate whether a filter system is working. If an ROM is breached, downstream EC/TDS sensors would register an increase in the measured EC, which would indicate system performance has declined or failed¹⁶⁸. Other filter stages such as WAC/SAC or SBA/WBA IEX resins may become less effective at removing ions from water when nearing saturation, and this difference may be indicated in conductivity measurements. Conductivity thus provides useful information on the status of a filtration system in the absence of more comprehensive water quality data.

pH and ORP sensors. Other types of water quality sensors, which do not appear to be implemented in any commercial POU systems, include pH¹⁶⁹ and ORP¹⁷⁰ sensors. Several types of pH sensors are available, of which the most common variation is the combination pH sensor. Two electrodes measure either side of a specially designed glass membrane, which contains a reference solution. The measured electrical potential is proportional to the

pH of the test solution¹⁷¹. Like conductivity measurements, pH measurements can also indicate the successful operation of a RO Or IEX system¹⁷². Like pH probes, ORP probes consist of a test and reference electrode. The test electrode either gains or loses electrons from the solution, resulting in a measurable potential across the two electrodes. ORP is measured in millivolts and depends on the substances present in the solution as well as their concentrations¹⁷³. These sensors are more complex and correspondingly more expensive, starting at around \$30 for the cheapest pH sensors¹⁶⁹ and \$90 for the cheapest ORP sensors¹⁷⁰. Although not present in water filters due to their cost, the combination of pH and ORP measurements can provide significant insight into the chemical makeup of water such as speciation of metals (e.g., $\text{Fe}^{2+}/\text{Fe}^{3+}$), oxyanions (e.g., $\text{H}_2\text{AsO}_4^-/\text{HAsO}_4^{2-}$), and multi-protic anions (e.g., $\text{HCO}_3^-/\text{CO}_3^{2-}$) as well as corrosivity (e.g., Langlier saturation index).

Future smart POU system using nanotechnology-enabled sensors

Nanomaterial-enabled sensors, also called nanosensors, are invented for high-efficacy, multiplex-functionality, and high-flexibility sensing applications¹⁷⁴. Interest in developing these sensors in POU applications originates from their potentials on facile, in-field contaminant detection. Many existing nanosensors are capable of sensing and monitoring the water safety. However, these sensors require further development into consumer- and operator-friendly products with the high compatibility of POU systems¹⁷⁴. While monitoring the water safety, nanosensors have ultralow multiplex detection and rapid analysis times, due to their novel properties^{175,176}. However, the great achievements in the laboratory and in the literature about nanosensors have seldom been translated to successfully commercialized products¹⁷⁴.

In principle, nanosensor is comprised of (1) a nanomaterial, (2) a recognition element, and (3) a mechanism for signal transduction¹⁷⁷. The interaction between the analytes and the recognition element will induce a detectable signal¹⁷⁴. The specificity of the nanosensor is endowed by detecting an intrinsic signal from the analyte or by employing highly specific recognition elements that ideally bind only to a given target¹⁷⁷. Moreover, the properties of the nanomaterial and the transduction method determine the sensitivity of the nanosensor¹⁷⁴.

Electrically based nanosensor typically employs nanomaterials such as silicon, noble metal nanoparticles (Pt, Ag, Au), carbonaceous nanomaterials (graphene, carbon nanotubes), and inorganic two-dimensional nanosheets due to their high conductivity and electrochemical stability¹⁷⁴. The electrically based nanosensors have enabled sensitive detection of waterborne contaminants such as *E. coli*¹⁷⁴. Figure 9 illustrates representative electrically based nanosensor architecture for environmental analyte detection. A glassy carbon electrode was functionalized via multiple steps, including the treatment with reduced graphene oxide, electro polymerization of pyrrole, electrodeposition of gold, and the co-deposition of silica and acetylcholinesterase¹⁷⁴. This nanosensor is capable of sensing organophosphorus pesticides.

In contrast to the electrochemical method, magnetic transduction shows less background signal and therefore can detect contaminants with low concentrations¹⁷⁷. The analytes that can then be detected are magnetically isolated via the functionalization of nanomaterials with analyte-specific biomolecules^{174,178}. Figure 10 illustrates representative magnetically based nanosensor architecture for environmental analyte detection. Combined magneto-fluorescence approach is applied to sense and detect bacteria via fluorophore labeled magnetic nanoparticles. Fluorescence and magnetic bacterial sensing are achieved by functionalizing specific antibodies of *E. coli* with magneto-fluorescent nanosensors.

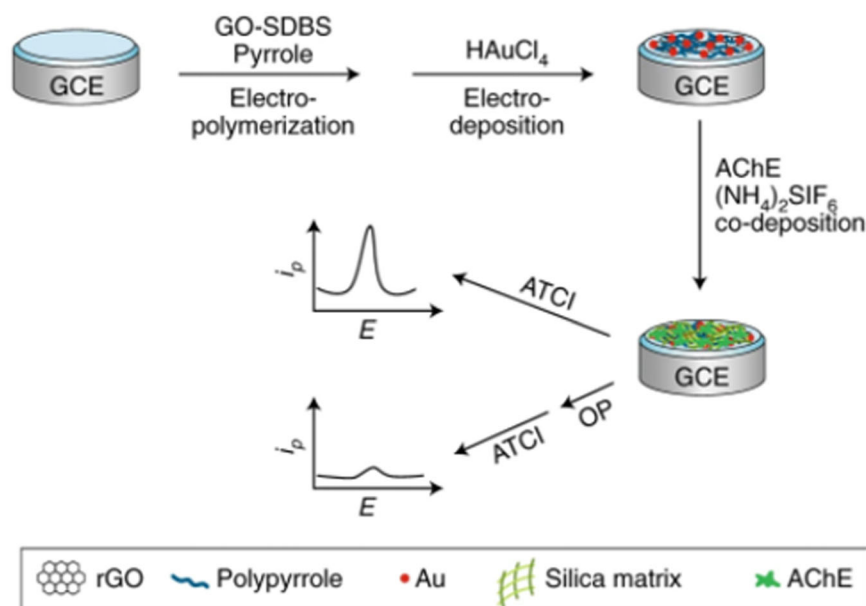


Fig. 9 Electrically based nanosensor architecture for environmental analyte detection. A glassy carbon electrode was functionalized via multiple steps, including the treatment with reduced graphene oxide, electro polymerization of pyrrole, electrodeposition of gold, and the co-deposition of silica and acetylcholinesterase (reprinted with permission from ¹⁸²; Copyright © RSC, 2014).

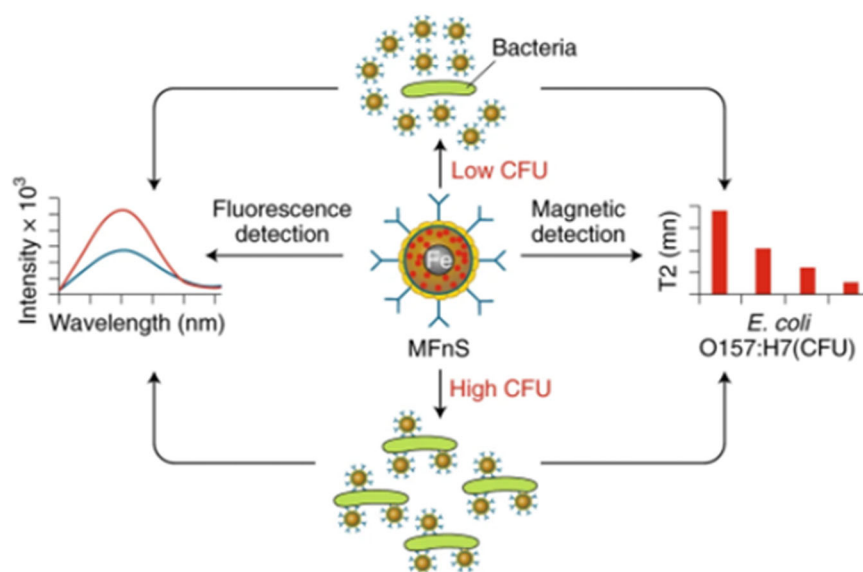


Fig. 10 Magnetically based nanosensor architecture for environmental analyte detection. Combined magneto-fluorescence approach is applied to sense and detect bacteria via fluorophore labeled magnetic nanoparticles. Fluorescence and magnetic bacterial sensing are achieved by functionalizing specific antibodies of *E. coli* with magneto-fluorescent nanosensors (reprinted with permission from ¹⁸³; Copyright © ACS, 2016).

Compared to traditional conductivity sensors or ORP sensors, nanosensors can be capable of detecting and monitoring a wider spectrum of contaminants by tailoring the sensor compositions^{174,179}. However, the challenges associated with transitioning novel nanosensors into POU system are particularly vexing due to the lack of capital sources powering product research, development, and marketing. In general, if a novel technology is to gain a foothold then the potential profits associated with it have to be considerable, while the risks of adoption must be acceptable¹⁷⁴.

CONCLUDING REMARKS

Current household tap water quality in the United States is as good as anywhere else where drinking water is treated to regulated quality. That said, violations for a wide array of regulated contaminants by public water systems, unregulated non-grid-tied groundwater wells, and unregulated emerging contaminants still pose serious acute and chronic health risks. For example, some very-high-profile cases of impaired municipal drinking water have occurred in recent years (e.g., lead in Flint, Michigan and Newark,

New Jersey). Moreover, long timelines for implementing new regulations in the U.S. cause some concern over the purity and healthfulness of municipal drinking water, especially with so many toxic, carcinogenic, endocrine disrupting, and pharmaceutically active chemicals known to be in drinking water's source waters. Treatment plants that use surface water as a source tend to have a higher frequency of violations compared to those using groundwater. For smaller systems, many of the violations are for lack of reporting versus reports of known violations, so the potential risk to the populations served is difficult to assess. As the size of treatment plants increase, the percent of violations and, in particular, those that use surface water both tend to decrease; however, the number of people potentially at risk is quite high due to the large populations served.

These well-documented drinking water violations, unregulated off-grid groundwater wells, and emerging contaminants all give rise to consumers' lack of confidence in drinking water quality and justify the use of POU drinking water treatment systems. Although there has been much research on the mechanisms and removal efficacies of the types of water treatment technologies employed in POU applications, most peer-reviewed studies are framed in the context of large-scale municipal or industrial treatment applications and few independent studies have evaluated their efficacy in POU water treatment applications. Components in commercially available POU water filter systems are highly commoditized and standardized across the industry. Sediment, KDF, AC (either GAC or ACB), RO, remineralization, and UVS are the most commonly employed technologies. This level of homogeneity in the production of filter systems is good in that it drives down costs to the consumer making POU water treatment widely accessible; however, the lack of regulations, monitoring and control of POU systems make it difficult to know if and when a POU system stops working as it was designed.

The smartness of POU water filters may be defined as their ability to perform tasks such as monitoring and reporting water quality, monitoring filter performance and expected lifetime, controlling filtration remotely, and connecting with consumers through personal smart devices. By this definition, currently there are no commercially available SMART POU water filtration products. Sensors providing water quality information is an essential feature for a water filter to become SMART. However, a SMART water filter is also expected to be connected to WiFi or Bluetooth and deliver the information to a mobile app. Interaction and control through the use of Internet is a key characteristic of any smart home technology. Future design and production of SMART POU water treatment systems should consider moving beyond timers and counters to flow meters and (at least) basic water quality sensors (e.g., EC/pH/ORP) along with Internet connectivity and interactive consumer apps. Finally, these technological innovations must be accomplished at very low cost to assure widespread accessibility for the most vulnerable and underprivileged populations.

DATA AVAILABILITY

The authors declare that no datasets were generated or analyzed during the current study.

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AUTHOR CONTRIBUTIONS

E.M.V.H. devised the project, the main conceptual ideas and proof outline of this review work. M.C., Z.F., and D.T. reviewed and drafted up the early manuscript. J.W. revised and improved the manuscript according to reviewers' comments. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

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