Real-time monitoring of residential water filters

Abstract

Drinking water is becoming increasingly scarce and polluted through anthropogenic influences, leading to more than one million deaths per year. Poor water quality is not only a concern in developing countries, but also in technologically advanced nations like the USA and China. Water filters, such as activated carbon or reverse osmosis membranes, can be used to significantly improve drinking water quality at the point of use. Often, such filters are certified for a specific volume through certification agencies. However, actual filter lifetimes depend on many site-specific factors and can deviate greatly from the certified lifetimes. Here, we present data from filter contamination experiments which found the breakthrough of organic contaminants after only 1/5 of the certified filter volume. The results also demonstrate that filter performance can be monitored in real time with affordable sensor solutions.

Water scarcity and diminishing quality

Almost two thirds of the global population suffer from severe water scarcity for at least one month per year.[1] Water shortages are further intensified through climate change and population growth.[2] Not only is water becoming a scarce resource, but its quality is also rapidly diminishing. Consequently, UNESCO identified water quality as one of the main societal challenges of the 21st century.[3] Water quality is not only a concern in developing countries, but also in technologically advanced countries like the USA and China. A recent study[4] pointed out that between 1980 and 2015, violations to the U.S. Safe Drinking Water Act more than doubled. The study further reports that in 2015, almost 21 million US citizens were exposed to municipal drinking water that violated health-related quality standards.

Common water pollutants

What are some of the most common pollutants that render our seas, rivers, lakes, groundwater and tap water unsafe – or even unusable? As most pollutants result from human activity, this varies greatly from region to region and depends on anthropogenic and environmental factors and influences. Among the most common pollutants are bacteria, viruses, fertilizers, pesticides and herbicides, pharmaceutical products, by-products of fossil fuel processing, disinfectants and heavy metals. While some of these

[1] Mekonnen and Hoekstra, 2016, Sci. Adv. https://www.science.org/doi/10.1126/sciadv.1500323

[2] https://www.unwater.org/water-facts/water-scarcity

[3] https://en.unesco.org/waterquality-iiwq/wq-challenge

[4] Allaire, Wu and Lall, 2018, PNAS. https://www.pnas.org/doi/full/10.1073/pnas.1719805115

pollutants have only minor effects on human health, others are highly toxic or even lethal.[5] In fact, unsafe water sources are estimated to be responsible for more than one million deaths each year.[6]

Water filters help improve water quality

Ideally, appropriate measures will be taken to prevent the contamination of our drinking water in the first place. However, this will represent an immense challenge in the decades to come. In the meantime, water filtration systems present an effective alternative. In many countries around the world, water is filtered and disinfected at the municipal water supply. Residential filtering solutions are often required to ensure safe drinking water in the absence of a clean municipal water supply, to reduce pollutants that enter the supply lines between the water supply facilities and the end-user or to remove disinfectants. Residential filtering systems are categorized as point-of-entry filters (e.g., filtering the main water supply line of a house) or point-of-use filters (e.g., under the sink or in a refrigerator) (see Figure 1). The most widely used residential treatment technologies are reverse osmosis membranes (RO), activated carbon filters (AC) or a combination of the two.

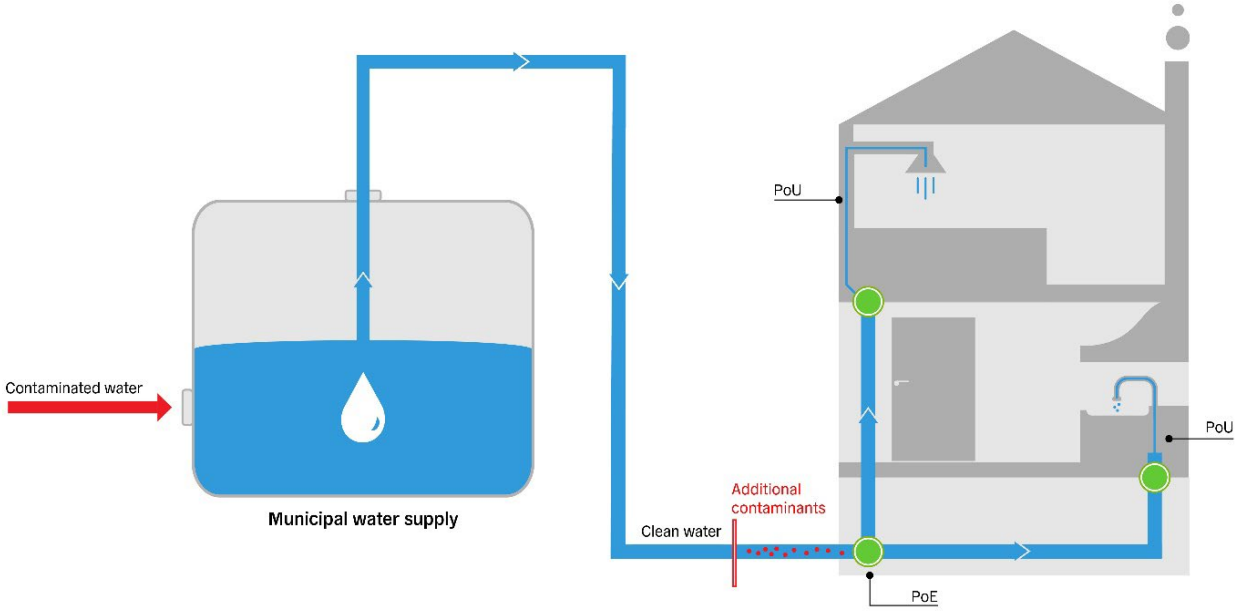

Figure 1: Schematic of water supply and point-of-use and point-of-entry filters

Activated carbon filters are based on the process of adsorption when contaminated water flows through the porous structure of the carbon material (see Figure 2A). Since the attracting Van der Waals forces between the non-polar carbon particles and non-polar pollutants – such as organic compounds – are stronger than the forces keeping the pollutants in solution, the pollutants adsorb to the surface of the carbon particles, leaving clean water behind. Van der Waals forces are only effective over very short distances, so a large surface area is required for efficient filtering. For that reason, the filter material is treated (activated) with hot gas to purify the charcoal and create microscopic pores within it, thereby creating very large surface-area-to-weight ratios.[7] AC filters can effectively remove by-products of disinfection and various chemicals, including volatile organic compounds. Special treatment of the charcoal also enables other contaminants, such as heavy metals, to be removed.[8]

[5] https://www.nrdc.org/stories/water-pollution-everything-you-need-know

[6] https://ourworldindata.org/water-access

[7] Dillon, Wilton, Barlow and Watson, 1989. Annals of Emergency Medicine. https://www.annemergmed.com/article/S0196-0644(89)80841-8/pdf

[8] Wu, Cao, Tong, Finkelstein and Hoek, 2021. npj clean water. https://www.nature.com/articles/s41545-021-00128-z

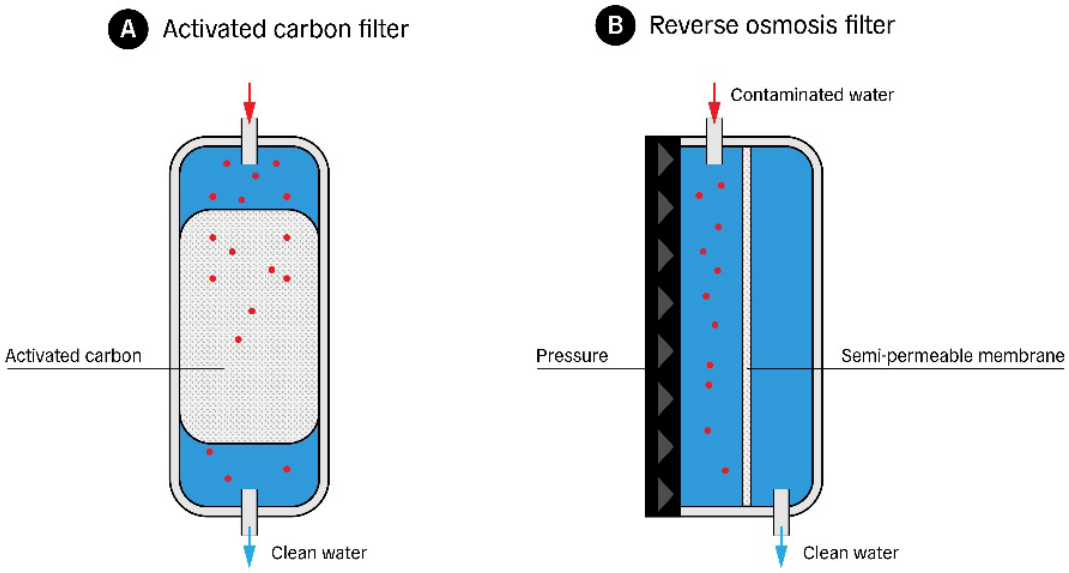

Figure 2: Activated carbon (A) and reverse osmosis (B) filters

Filters based on **reverse osmosis** apply pressure (e.g., with a pump or piston) to the contaminated water in order to overcome the osmotic pressure, thereby forcing the solvent (water molecules) to flow from the concentrated side of a fine-meshed, semi-permeable membrane to the "pure" solvent side, leaving behind the contaminants (Figure 2B). Given adequate pressure, thanks to their fine mesh, RO systems are very effective at removing various inorganic and organic pollutants, including bacteria such as *E. coli*.[8] However, while RO systems are generally more effective than AC filters at filtering contaminants, they are usually more expensive and require pre-filtering with sediment filters and AC filters to prevent clogging and membrane fouling.

Limitations of current filtration systems

Unfortunately, not everyone can afford such filtering solutions – or is even aware of the poor quality of their drinking water. In the USA and China, on the other hand, residential filtering solutions are very popular due to a combination of poor drinking water quality and mistrust in municipal water supplies. In a recent survey conducted by the US public health organization NSF International,[9] 58% of the respondents reported that they use water treatment systems. However, most of those surveyed rely on filters that come with their house, sink or refrigerator. This is problematic because filters are designed to reduce specific pollutants and should be chosen accordingly. Filter vendors can have their filters certified by an accredited organization such as NSF International, the Water Quality Association[10] or Underwriters Laboratories,[11] who challenge the filters with water containing a defined mixture of contaminants while monitoring the filter's efficiency over time. This yields a volume or capacity rating (in gallons or liters) for each tested filter, that is, a volume after which the end-user should replace the filter cartridge. While this might be a useful indicator for when to change the filter in some cases, it is questionable in many others because filter lifetime is highly site-specific. The performance of the same filter can vary greatly depending on the type and concentration of pollutants, pH value and temperature. As a consequence, filters are likely to not be exchanged at the right time, but either too late (unsafe) or too early (uneconomical).

[9] https://www.nsf.org/

[10] https://wqa.org/

[11] https://www.ul.com/

The solution: Real-time filter monitoring and smart filters

The straightforward solution would be smart filters that monitor water quality to warn the end-user when the filter is nearing the end of its life or once contaminants have breached the filter. This concept is experimentally demonstrated by equipping an activated carbon filter with water quality sensors before and after the filter (see Figure 3). These sensors measure total organic carbon (TOC), which is a general measure of the amount of carbon contained in (harmful and harmless) organic compounds in the water flowing into and out of the filter. Water containing high levels of organic contaminants is constantly fed into the filter. Initially, the sensor installed behind the filter detects clean water, free of organic contaminants (i.e., the filter is working properly). In the experiment, the sensor behind the filter detected a sudden rise in organic contaminants after approximately 220 L, indicating that the filter was saturated and not working. While this specific filter is certified for a volume of approximately 2,400 L water, it can actually fail after only 220 L, because contamination levels in the water are relatively high (5 mg/L, corresponding to roughly 1–10x the expected concentration in municipal drinking water). This experiment demonstrates two important points:

1. **The certified filter volume is indeed only a very rough indicator of a filter's lifetime. The actual lifetime will likely differ and is site-specific.**
2. **A TOC sensor can be used to monitor filter efficiency and to indicate an approaching failure in real time.**

Unfortunately, sensors and instruments for monitoring water quality parameters and contamination levels are very expensive and bulky, rendering them unfeasible for use in residential filter monitoring. Some filtration systems use timers, flow meters and pressure sensors with some success to try and derive filter efficiency from these surrogate parameters. However, no smart residential water filters currently exist that would allow real-time performance monitoring, as is common practice with air quality monitoring and ventilation in other home appliances.[8]

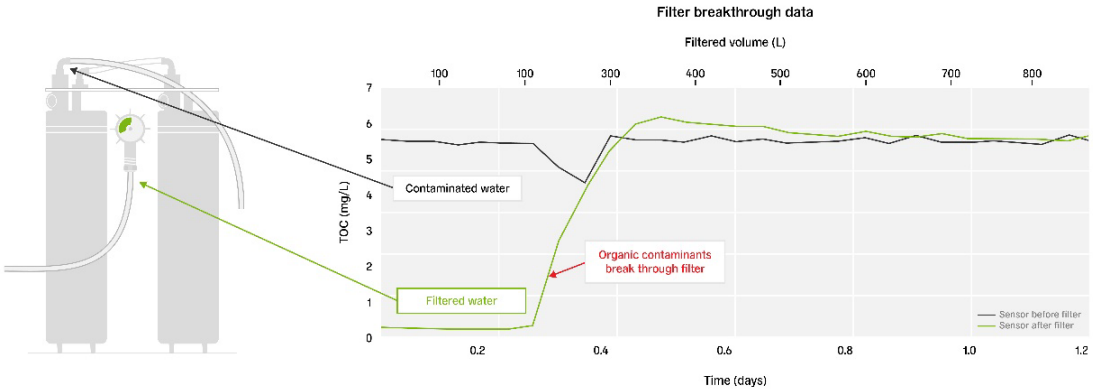

Figure 3: Data from filter intrusion experiment. Data from the sensor installed in front of the filter is denoted in black, while data from the sensor installed behind the filter is shown in green.

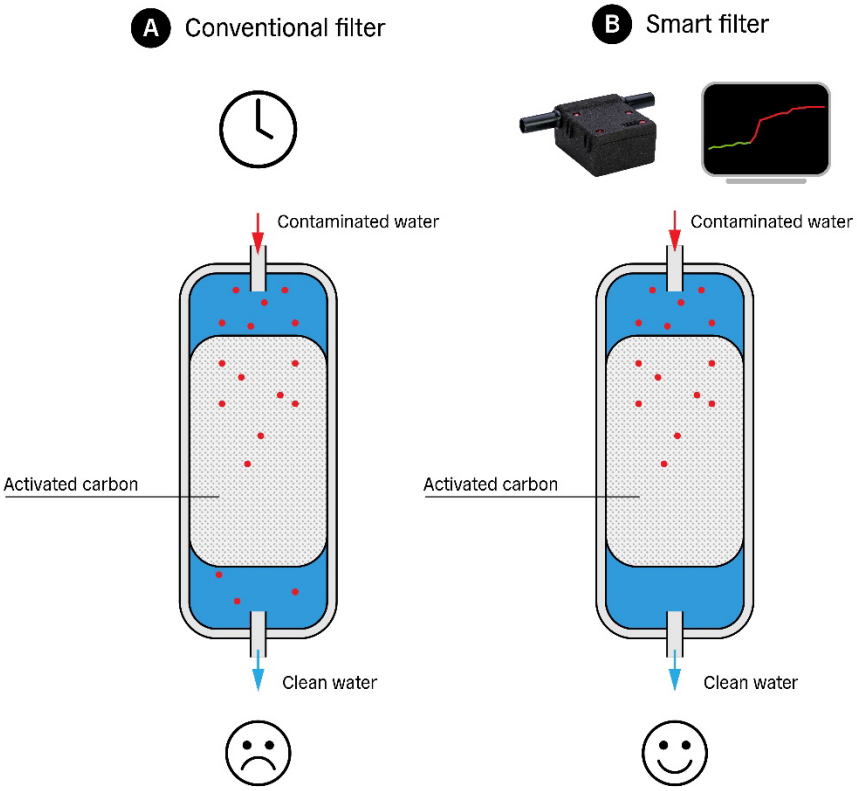

Figure 4: Schematic of traditional filter versus smart filter

Sensirion's contribution to smart water filters

Sensirion's new SWT50 sensor (see Figure 5) is the first product in the family of water quality sensing. The sensor uses a UV-absorption-based measurement principle to measure TOC in water. Its low price and small form factor make it ideal for applications such as filter monitoring.

Figure 5: Sensirion SWT50 sensor

