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Class 100 Filtration Mechanism for Household-level Remediation to Eliminate Groundwater Contaminants

Adhit Mandal

The Shri Ram School, Aravali, Gurgaon, Haryana, India, 122002; adhit.mandal29@gmail.com

ABSTRACT: This research paper focuses on providing potable drinking water for low-income households, where treated tap water from municipal sources is unavailable. It leverages multi-stage, ultra-filtration for a range of physical, chemical, and microbiological contaminants in groundwater, resulting from manmade activities like industrial pollution, untreated sewage water, fecal sludge, waste landfills, mining, grey water from homes not connected to the drainage system, and natural reasons like the presence of minerals, resulting from the dissolution of rocks. The water does not meet quality standards, with high levels of suspended particles, fluoride, chloride, arsenic, nitrates, sulfates, phosphates, metals (iron, manganese, lead, mercury, cadmium, chromium), organic contaminants (pesticides, herbicides, oil, hydrocarbons), and microbes. Using easily available, affordable materials and leveraging a Class 100 filtration mechanism, contaminated water samples were passed through separate multi-stage ultrafiltration columns with layers of coarse sand grains, slag wool, pink sand, activated charcoal, and ceramic cones. When water flowed slowly through the filtration column, the physical, chemical, and microbiological contaminants were removed. This mechanism is low-maintenance, does not require electricity, and the media need to be cleaned after 30-40 days, with replacement of only the activated charcoal, thus providing a practical approach to address multiple contaminants in drinking water.

KEYWORDS: Chemistry, Materials Chemistry, Class 100 Water Filtration, Water Contamination, Water Purification.

Introduction

The sustainability of drinking water sources has become a growing challenge, particularly in developing nations, due to increasing population, inadequate water management, and the inevitable crisis of climate change. According to estimates by the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) in 2021, approximately 2 billion people worldwide, or a quarter of the global population, lacked access to clean water.[1] As per another estimate in 2024, 4.4 billion people across 135 low- and middle-income countries — over half of the world's population — do not have safe household drinking water, with fecal contamination as the primary limiting factor affecting them.[2] In a large country like India, about 30% of urban households, mostly those living in slums, and 90% of rural households still depend entirely on untreated surface water or groundwater.[3]

Groundwater quality has deteriorated due to various anthropogenic activities, including industrial pollution, sewage, waste landfills, and mining. Additionally, there are naturally occurring or geogenic reasons for water contamination, resulting from the presence of natural minerals that are caused by the dissolution of soluble rock products. Groundwater may contain several hazardous contaminants and does not meet the standards specified by international organizations, such as the WHO,[4] or the country-specific guidelines published by regulatory agencies. These standards cover a range of parameters, including physical and chemical metrics, microbiological parameters, and other aspects of water quality.

The kind of contaminants and the degree of contamination varies across countries and regions within a country, with quality issues like elevated levels of fluoride, arsenic, iron, manganese, chlorides, nitrates, sulfates, phosphates, heavy metals (lead, mercury, cadmium, chromium), organic contaminants (pesticides, herbicides, oil, hydrocarbons), suspended particles, microbes, and hardness minerals like calcium and magnesium.

In several countries, especially in rural areas, village ponds play a crucial role in maintaining the quality of groundwater, which is often drawn from hand pumps and borewells. The pond water becomes contaminated because households and community water points in many places are not connected to the drainage network. Hence, grey water (from bathing, washing clothes, and utensils) stagnates outside houses or at water points. Greywater contamination is also an issue in urban slums. Fecal sludge, biosolids, and untreated wastewater from nearby industrial activity further deplete the water quality in ponds. Most often, the users are not even aware of the presence of the contaminants and their side effects.

Prolonged consumption of contaminated drinking water has several repercussions. High levels of dissolved solids can impact health by causing gastrointestinal issues, kidney problems, and even affecting the taste and odor of the water, making it less palatable and sometimes leading to dehydration. High fluoride levels can cause fluorosis, which is typically diagnosed at a more advanced stage and is irreversible. Dental fluorosis causes loss of luster and shine of the dental enamel. Skeletal fluorosis leads to severe pain associated with rigidity and restricted movements of the cervical and lumbar spines, knees, pelvis, and shoulder joints, often leading to crippling deformity. Arsenic causes skin diseases and cancer. Chlorides combined with sodium cause high blood pressure. Nitrates in water cause

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thyroid and birth defects like methemoglobinemia or blue baby syndrome, where the ability of red blood cells to carry oxygen is reduced and can lead to serious illness or death. Sulfate, when combined with magnesium, may cause gastrointestinal issues. Consumption of heavy metals in drinking water can cause neurological problems, kidney damage, and cancer. The pathogens cause waterborne diseases like cholera, typhoid, and dysentery.[5-9]

The goal of this research is to identify suitable natural and sustainable filtration media for creating a household-level water treatment system, especially in low-resource settings, such as rural areas and urban slums, to deliver water quality comparable to that of households with a municipal treated water supply.

Methods

Section 1: Contaminants in water samples:

Water samples, drawn from hand pumps and being used for drinking purposes, were collected from villages and urban slums in India. These were collected from areas where water issues exist, such as high dissolved solids and foul odors, community water points not linked to drainage systems, stagnant and dirty water close to the water points, and industrial activity nearby that releases untreated wastewater into the groundwater.

I took four different samples of water from urban and rural sources, tested the samples for all characteristics (physical, chemical, metal, microbiological) through an accredited lab, and compared them to the specifications published by the Bureau of Indian Standards (BIS) IS: 10500.[10] The first water sample was taken from the municipal water in urban areas, which is treated water. In ideal situations, all other samples of water should meet at least these standards. The quality parameters of this sample were compared to those of water samples from different sources, which are expected to have high contaminants due to factors such as natural reasons, proximity to stagnant, dirty water, including grey water, fecal sludge, and untreated water from industrial activity. The samples chosen were as follows:

- Sample 1 (S1) – Municipal water supply to urban households
- Sample 2 (S2) – Hand pump water from a village where stagnant grey water and sludge are present close by, because the main drainage system is not adequately connected to all houses
- Sample 3 (S3) – Hand pump water in an urban slum where stagnant grey water is present close by, caused by a lack of connection of the community water point with the main drainage system
- Sample 4 (S4) – Hand pump water in a village where untreated water from industrial activity has seeped into the groundwater. The industrial activity in the vicinity comprises metal and alloy factories, dyeing units, plastic manufacturing facilities, chemical processing plants, and electronics and battery manufacturing plants. In several cases, smaller units occasionally do not adhere entirely to wastewater treatment standards and thus contribute to groundwater contamination.

Section 2: Results of testing of water samples before filtration:

The characteristics that did not meet BIS standards in any one of the samples are being discussed further in this report. The characteristics that met the BIS standards have not been discussed further. The test results for S1, municipal water supply to urban households, met all the specifications as per BIS standards for the parameters tested. S2, S3, and S4, however, had different kinds of contaminants, some at alarmingly high levels.

Physical characteristics: The test results for S2, collected from a hand pump in a village with stagnant grey water and sludge in the vicinity, indicated a foul smell. The odor in the other two contaminated samples was agreeable. The total dissolved solids (TDS) were higher than the BIS standard of 500 maximum in all three contaminated samples, as showcased in Figure 1. The levels of TDS were 3256 mg/L, 985 mg/L, and 1590 mg/L in S2, S3, and S4, respectively, as against the prescribed standard of a maximum of 500 mg/L.

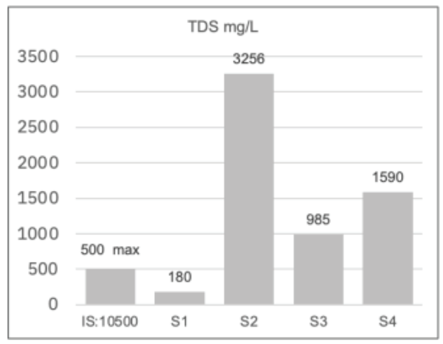
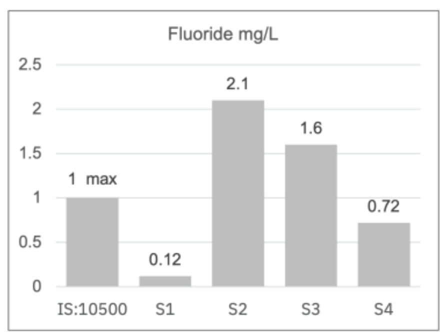
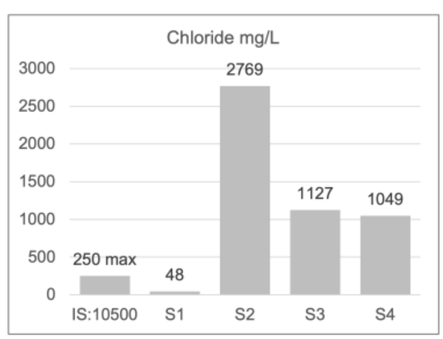


Figure 1: TDS levels in drinking water samples vis-à-vis BIS standards. TDS in S2 was more than 6 times, in S3 almost twice, and in S4 more than thrice the industry standard (maximum 500 mg/L) prescribed, while the municipal water sample S1 adhered to the standard.

Chemical analysis: According to the laboratory test results on the water samples, the key contaminants in S2, S3, and S4 were fluoride, chloride, nitrate, and sulfate.





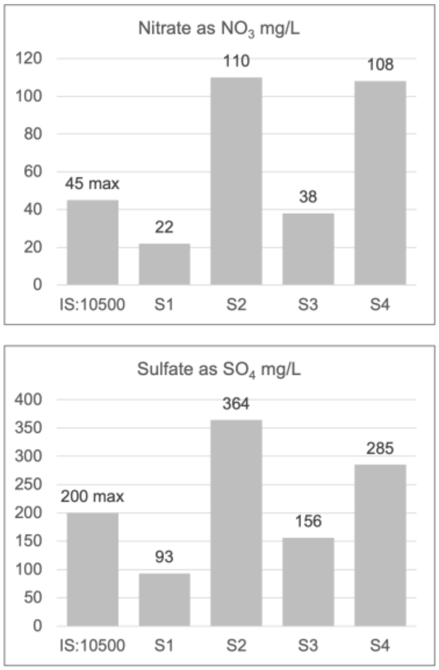


Figure 2: Results of chemical (fluoride, chloride, nitrate, and sulfate) analysis of drinking water samples. While S1 from the municipal source met all parameters for chemical analysis, S2 was contaminated with all four chemicals, S3 was contaminated with fluoride and chloride, and S4 was contaminated with chloride, nitrate, and sulfate.

As evident from Figure 2, the level of contamination of S2 was the highest amongst all samples – fluoride at double the level (2.1 mg/L), chloride at more than ten times (2769 mg/L), nitrate at more than double (110 mg/L), and sulfate at 1.8 times (364 mg/L) the maximum levels prescribed as per the industry standards. Major chemical contaminants in S3 were fluoride (1.6 mg/L) and chloride (1127 mg/L), with the latter at more than four times the industry standards. S4 had almost four times the prescribed limit of chloride (1049 mg/L), more than twice the limit of nitrate (108 mg/L), and high levels of sulfate (285 mg/L).

Metal analysis: The results of the presence of metals are showcased in Figure 3. The test results showed that iron and lead levels in all samples were way above industry standards. Iron levels were 1.1 mg/L, 0.9 mg/L, and 1.5 mg/L in S2, S3, and S4, respectively, as compared to the prescribed standard of a maximum of 0.3 mg/L. The levels of lead were 0.05 mg/L, 0.03 mg/L, and 0.05 mg/L in S2, S3, and S4, respectively, in comparison to the prescribed standard of a maximum of 0.01 mg/L.

Moreover, alarming levels of cadmium in S2 were found, 3.09 mg/L as compared to the industry standard of 0.01 mg/L. Chromium and uranium levels were unusually high in S3, chromium levels at 4.1 mg/L, with the maximum limit prescribed at 0.05 mg/L, and uranium at 4.1 mg/L, with the maximum limit prescribed at 0.03 mg/L. This was mainly an outcome of the untreated water from industrial activity seeping into the groundwater.

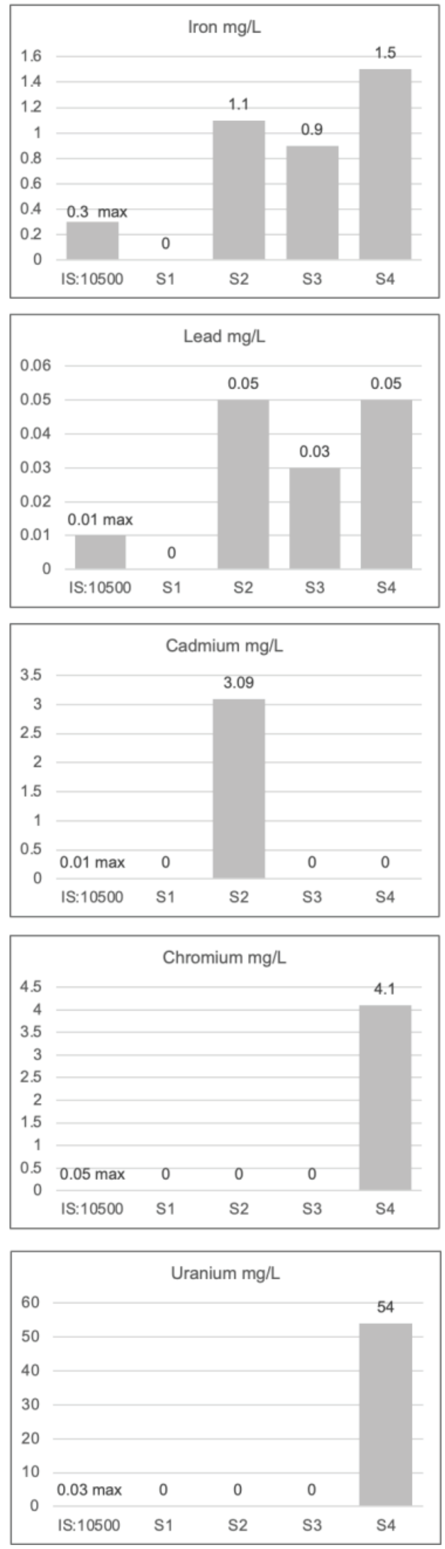


Figure 3: Results of metal analysis of drinking water samples. Iron and lead levels were higher than acceptable norms in all three contaminated samples. Cadmium level in S2 was 300 times the permissible limit. S4 was found to have abnormally high levels of chromium and uranium contamination.

Microbiological analysis revealed coliform contamination in S3, indicating that the water was not suitable for drinking purposes.

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Section 3: Filtration mechanism for addressing multiple contaminants:

To address the issue of varying contaminants across locations, my solution is based on Class 100 water filtration, a multi-stage ultrafiltration system for water, utilizing principles of physical, chemical, and microbiological processes. "Class 100" implies a system designed to minimize particulates to a very high degree and remove microscopic contaminants.

Using natural materials for Class 100 water filtration requires carefully selecting materials that are most effective in removing physical and chemical contaminants, as well as bacteria, at a micro scale.

Figure 4: Materials used in the filtration column for water purification. Layers of coarse sand, slag wool, pink sand, activated charcoal, and ceramic cones, available in bulk locally in all environments, were chosen for further experimentation.

Five layers of different materials were selected to create a filtration column, with a focus on adsorption. The layers included coarse sand grains, slag wool, pink sand, activated carbon, and ceramic cones, as exhibited in Figure 4. The ultrafiltration mechanism works through physical filtration, where pollutants are trapped in the filtering media as water passes through, and absorption filtration, where contaminants are adsorbed into the filtration media. The adsorbing media were selected based on their high thermal stability, small pore diameters, high exposed surface area, and hence high surface capacity for adsorption.

The filtration column for a household of 4-5 members can be designed to be approximately 2 feet tall. Each layer is approximately 4 inches thick, ensuring a water flow rate of approximately 1.5 to 2 liters per hour. I experimented with various thicknesses of each layer. I found that a thickness of approximately 4 inches is suitable for slowing down the water flow and providing ideal contact time with the filtration media. The raw contaminated water is fed into the filtration column from the top and moves downward through the layers due to the force of gravity. The treated, purified water is collected from the outlet at the bottom of the filtration system.

Section 4: Filtration Column layers (in descending order):

Layer 1 - Coarse sand grains (approximate grain size of 1mm)

These are available in bulk locally in all environments. For this project, river sand was used, which has a high surface area, surface charges (especially from clay and oxide coatings), the presence of functional groups for chemical binding, and pore spaces that trap microbes and particulates. 70-90% of river sand is composed of crystalline silica (SiO_2). While the silica itself is not highly adsorptive, its large surface area and porosity help trap suspended solids. The surface can become slightly negatively charged, enabling the adsorption of positively charged metal ions, such as lead and chromium. The small amounts of clay minerals present in sand, such as kaolinite and montmorillonite, make it highly adsorptive due to its high surface area, negative surface charges that attract positively charged ions (like heavy metals), and the presence of functional groups (e.g., OH^-, $Si\text{-}O^-$, $Al\text{-}O^-$) that bind contaminants. Sand also has trace amounts of iron and aluminum oxides and hydroxides (Fe_2O_3, $FeOOH$, AI_2O_3, $Al(OH)_3$).

The river sand was rinsed thoroughly in clean water and then dried in the sun.

The sand media helps in:

• Removing organic matter by trapping suspended particles (like plant material, algae) as well as dissolved organic compounds (adsorbs natural organic matter from decaying plants and animals).

• Removing bacteria and pathogenic microorganisms. While sand does not kill bacteria, it traps them, and over time, a biofilm of microorganisms that grows in the sand can break down the organic material. This gets removed when the media of the column is cleaned as part of the maintenance cycle.

• Removing organic sludge that accumulates from surface runoff or decaying biological material (like fecal sludge).

• Partially capturing small amounts of oil and grease, particularly if they are bound to other particles or sediments.

• Adsorbs heavy metals and is effective for the removal of chromium (VI) and lead.

• Adsorbing arsenic and phosphates.

Layer 2: Slag wool

Slag wool is a by-product of steel production. It is a fibrous material made from molten slag that has been spun into fibers. It features a dense fiber matrix, a porous structure, and a high surface area, making it ideal for adsorption. Its chemical composition includes SiO_2 35–50%, calcium oxide (CaO) 10–30% which enhances chemical reactivity with heavy metals like lead and copper, aluminum oxide (Al_2O_3) that facilitates adsorption sites via surface hydroxyl ($-OH$) groups, magnesium oxide (MgO) which facilitates ion exchange and neutralization reactions, and iron oxides (Fe_2O_3/FeO), that can adsorb anions like phosphate and arsenate. It also assists in physical filtration by acting as a fine mesh, especially right below the sand layer.

It helps in the following:

• Effective adsorption of certain metals, especially heavy metals like lead, cadmium, zinc, copper, nickel, chromium, and arsenic, via ion exchange

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• Removing phosphates that bind to the iron, aluminum, and calcium oxides

• Removing suspended solids like silt, sand, and larger particulates that could cloud water by acting as a physical barrier to sedimentation, thereby reducing turbidity

• Trapping small organic particles (like plant material and algae)

• Absorbing oils, greases, dyes

• Partially removing bacteria and microorganisms (if they are attached to larger particles); however, it does not kill pathogens or remove dissolved biological contaminants.

Layer 3: Pink sand

Pink sand is composed mainly of quartz, feldspar ($KAlSi_3O_8$, $NaAlSi_3O_8$, $CaAl_2Si_2O_8$), calcium carbonate ($CaCO_3$), and traces of iron oxides (Fe_2O_3, Fe_3O_4). This enhances its adsorption capabilities compared to river sand. In filtration processes, it helps in the following:

• Slowing down the flow of water in the filtration column significantly. This is one of the major reasons for adding this layer.

• Reducing suspended solids and organic matter further – the fine-grain size of pink sand provides a large surface area for good bacteria to attach to and thrive, aiding in water filtration

• Partially removing bacteria

• Adsorbs traces of heavy metals, especially iron, manganese, and arsenic, as well as phosphates

• pH buffering by neutralizing acidic water

Before placing a layer of activated charcoal, a thick bundle of Grade 1 filter papers was tightly packed to ensure that grains of pink sand do not get pushed down into the activated charcoal below.

Layer 4: Activated carbon

Activated carbon is an adaptable adsorbent due to its properties, including a large surface area, high pore volume, diverse pore structure, extensive adsorption capacity, and a high degree of surface reactivity. It is prepared from various carbonaceous source materials, such as agricultural waste like coconut shells, wood (mostly bamboo cane and acacia), agricultural residues (like rice husk, betel nut husk, sugarcane bagasse), seeds (mango, papaya), and shells (like tamarind shell, cashew nutshell, acorn shell, banana peel, palm kernel shell). The higher adsorption capability of activated carbon depends on porous characteristics such as surface area, pore size distribution, and pore volume. The porous structure of activated carbon forms during the carbonization process, and it further develops during the activation process. The pore system of activated carbon differs from one another, and individual pores vary in size, ranging from less than a nanometer to thousands of nanometers.

In my filtration column, I have used activated charcoal made from coconut shells, which has a higher density of micro-pores as compared to other forms of activated carbon, meaning it has a higher surface area and porosity. This layer helps to:

• Adsorb fluoride, arsenic, chlorides, heavy metals (like iron, lead, mercury, copper, zinc, cadmium, nickel), trace metals (chromium, uranium).

• Remove dissolved organic compounds (pesticides, petroleum-based products, industrial chemicals, natural organic matter, organic dyes from many industries, such as the textile, cosmetics, leather, printing, rubber, and food industries), chlorine and chlorinated compounds, volatile organic compounds (benzene, toluene, xylene), and pharmaceutical residues.

• Absorb odor-causing compounds (mostly industrial pollutants) and inorganic compounds like sulfates, improving taste.

• Address hardness and salinity issues.

• Adsorb microbial contaminants to some extent within the microscopic pores of the carbon.

Layer 5: Ceramic cones.

Ceramic cones are made from locally sourced clay materials, including kaolin clay, alumina, silica, feldspar, and even sawdust and rice husks. They are fired at controlled temperatures to create porous structures ideal for filtration. In this filtration column, cones made of kaolin clay are used. This layer enables mechanical filtration, adsorption, and even antimicrobial action. It is ideal for filtering out dissolved inorganic compounds (such as salts and nitrates) and trapping bacterial contaminants in its microscale pores. Ceramic cones can filter out particulates as small as 0.2–0.5 microns. They are durable and can be cleaned multiple times, extending their usability. Moreover, this layer provides support for all the previous layers of media, ensuring that the smaller particles do not clog the outlet pipe.

For further research, these layers were used to create a filtration column in a clean plastic container, as exhibited in Figure 5.

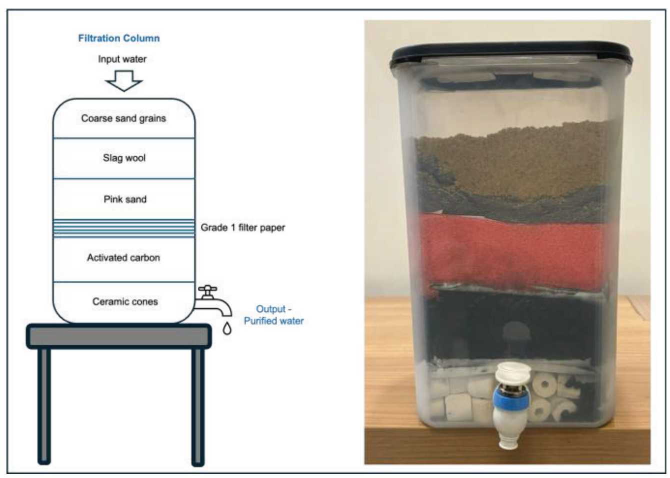

Figure 5: Depiction of the filtration column created for water purification. The layers of materials were assembled to create a filtration column for treating contaminated water, with each layer being approximately 4 inches in thickness, providing ideal contact time with the filtration media.

During the experiments, it was observed that the efficacy of the filtration column decreased after 30 to 45 days. Hence, all the media needs to be replaced or cleaned. The layer of activated charcoal in the filtration column was replaced, while the rest of the media was boiled separately in water, dried in the sun, and then reused.

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Result and Discussion

The three contaminated water samples were filtered through three separate filtration columns. The water collected from the respective outlets of the columns was tested separately through an accredited lab. The pH levels post-filtration were examined, but since they were well within the range prescribed by BIS across all three samples, they were not tabulated in the subsequent analysis.

Post filtration, the foul odor in S2 was eliminated. The TDS levels, which were higher than the industry standards across S2, S3, and S4, were brought down to 126 mg/L, 53 mg/L, and 102 mg/L, below the industry standard of 500 mg/L. From Figure 6, it is evident that the TDS levels decreased by approximately 95% in all three samples.

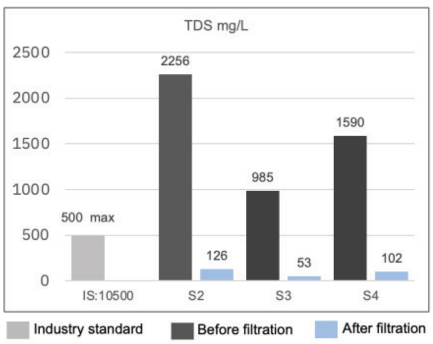

Figure 6: Comparison of TDS levels in drinking water samples before and after filtration. Post filtration of each contaminated through the filtration columns, it was observed that the TDS levels were brought down to levels that were much lower than the prescribed industry standard.

A chemical analysis post-filtration indicated a significant drop in contamination levels. S2, which had high levels of fluoride, chloride, nitrate, and sulfate, witnessed a drastic reduction in contamination levels, meeting industry standards. Fluoride levels went down from 2.1 mg/L to 0.65 mg/L. Chloride levels significantly reduced from 2769 mg/L to 48 mg/L. Nitrate levels fell from 110 mg/L to 42 mg/L. Sulfate levels fell from 364 mg/L to 140 mg/L. These results are showcased in Figure 7.

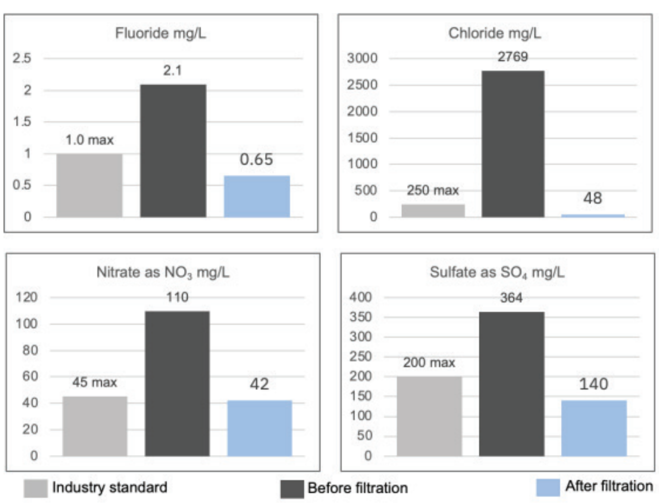

Figure 7: Comparison of contamination levels of chemicals in S2 before and after filtration. The high contamination levels of fluoride, chloride, nitrate, and sulfate in S2 were all addressed post-filtration and fell to levels below the prescribed industry standards.

S3, which had high levels of fluoride and chloride, showed an 82% and 96% decrease, respectively, with both levels meeting industry standards post-filtration, as evident from Figure 8. Fluoride levels went down from 1.6 mg/L to 0.3 mg/L. Chloride levels significantly reduced from 1127 mg/L to 41 mg/L.

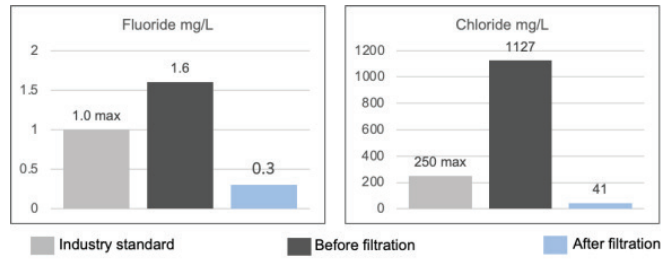

Figure 8: Comparison of contamination levels of chemicals in S3 before and after filtration. Fluoride and chloride levels in S3, which were higher than the prescribed norms, were treated effectively, post-filtration.

S4, which had high levels of chloride, nitrate, and sulfate, experienced a drastic reduction in contamination levels, meeting industry standards, as shown in Figure 9. Chloride levels fell from 2769 mg/L to 48 mg/L, nitrate levels fell from 110 mg/L to 42 mg/L, and sulfate levels fell from 285 mg/L to 128 mg/L.

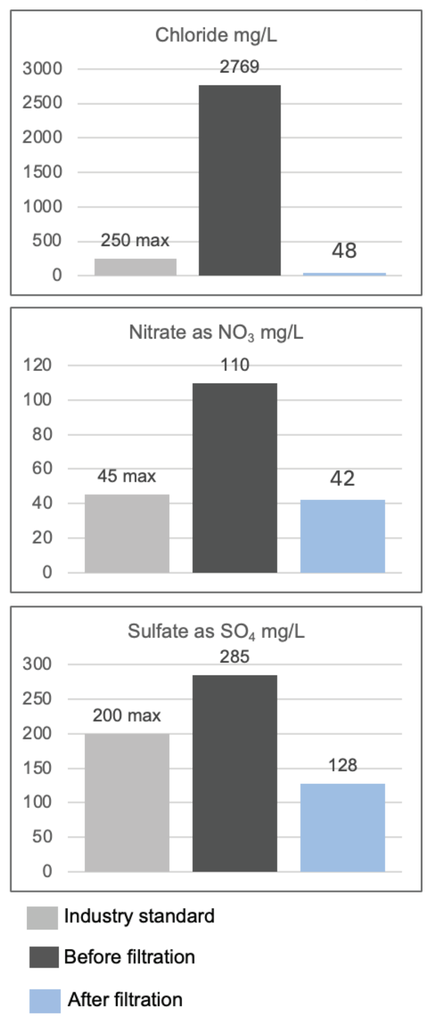

Figure 9: Comparison of contamination levels of chemicals in S4. S4, which had high levels of chloride, nitrate, and sulfate, showed a significant decrease in the levels of these chemicals, with levels meeting industry standards post-filtration.

Thus, the metal analysis results also show a significant reduction in contamination levels. The iron and lead levels, which were high in all three samples, fell to levels that meet industry standards. However, the chromium, cadmium, and uranium levels, although significantly lower post-filtration, did not meet the BIS standards. Chromium level in S4 fell by 75% from 4.08 mg/L to 1.02 mg/L; however continued to be higher than the industry standard of 0.05 mg/L maximum. Cadmium level in S2 fell by 97% from 3.09 mg/L to 0.08 mg/L; however continued to be higher than the industry standard of 0.01 mg/L maximum. Uranium level in S4 fell by 98% from 53.9 mg/L to 1.08 mg/L, but continued to be higher than the BIS standard of 0.03 mg/L maximum. Hence, the water samples S2 and S4 were unsafe for consumption due to very high contamination levels of heavy metals. To reduce these contaminants to meet industry standards, certain activating agents will need to be researched further and added to the filtration column.

S3, which had the presence of *E. coli* and coliforms, showed that these contaminants were eliminated post-filtration, as indicated by the laboratory test results.

Conclusion

Multiple factors influence groundwater quality. These include local geology, land use, climatic conditions, patterns and frequencies of rainfall, and anthropogenic activities such as the use of fertilizers and pesticides in agriculture, the disposal of domestic sewage and industrial effluents, and the extent of groundwater resource exploitation. Low-income households cannot afford commercially available solutions, such as reverse osmosis systems, for installation in their homes. High levels of dissolved solids, fluoride, chloride, arsenic, nitrates, sulfates, phosphates, metals (such as iron, manganese, lead, mercury, cadmium, and chromium), organic contaminants (including pesticides, herbicides, oil, and hydrocarbons), and microbes in drinking water have toxicological and epidemiological implications.

Home-built water filtration solutions, based on easily available and affordable filtration media, can help resolve the issue of drinking water quality for low-income households, for whom commercial solutions are unaffordable. Given that the type of contaminants and degree of contamination vary across regions, a home filtration solution must utilize media that address multiple contaminants to provide a safe source of water. This is evident from the results of the water samples, which had multiple contaminants, tested at an accredited laboratory before and after filtration through a series of media in a filtration column.

A major advantage of the filtration mechanism examined in my project is that it is gravity-based and does not require any electricity. The materials used in the column are low-cost, easily available, require minimal maintenance, and address a wide variety of contaminants, including physical, chemical, heavy metals, and microbiological. Initial material cost for a single filtration column to filter roughly 10 liters per day works out to approximately INR 700-800 (less than USD 10). The replacement cost for approximately 30 days is only for activated charcoal, the cost of which is approximately INR 100-150 (USD 1.2-1.8). The contaminants in the different water samples used in the project were varied. By leveraging low-cost, readily available, and low-maintenance media for water treatment, households in resource-constrained communities can address the issue of multiple contaminants in water for human consumption.

Going forward, some areas will require further research. There are potential limitations to the filtration mechanism for high concentrations of certain contaminants, such as heavy metals. In case the contamination levels, especially of heavy metals, are way too high, this filtration mechanism is unlikely to bring them down to the WHO standards, as was the case in two of my sample results post-filtration. The cadmium level in S2 and the chromium and uranium levels in S4, although they fell significantly, did not reach the levels specified in the BIS standards. Additional research and experiments are needed to determine the type of agents required and whether they can be incorporated into this project or if specific technical interventions are necessary.

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Authors

Adhit Mandal is a student at The Shri Ram School Aravali, Gurgaon, India. He is a passionate environmentalist and researcher in the areas of renewables and sustainable materials. He aspires to join a prestigious college course in Materials Science Engineering. He loves participating in competitions that give him an opportunity to research innovative solutions for real-life global issues.