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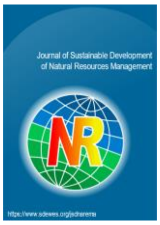

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Original Research Article

Performance Evaluation of an Activated-Sand-Based Point of Use Water Treatment System for Removal of Physicochemical Contaminants from River Water

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ABSTRACT

Waterborne diseases are a significant health concern in Kenya, particularly for children under the age of five. This is primarily due to inadequate and affordable infrastructure for water treatment. A large portion of the water in Kenya does not meet the drinking water standards set by the Kenya Bureau of Standards and World Health Organization, which poses a considerable risk for waterborne diseases. Considering this, the study aimed to develop a low-cost, activated-sand-based water treatment system for households in rural and informal settlements in Kenya, where access to clean water is limited. The research was motivated by the pressing need for an affordable and efficient water treatment solution in these areas with a focus on removal of physicochemical contaminants from water. The hypothesis proposed was that an activated-sand filter system, enhanced with silver for additional purification, could serve as an effective point-of-use water treatment option that is both cost-efficient and sustainable. To test this hypothesis, the study utilized a range of methods. The physical and chemical properties of the filter materials were characterized using X-ray fluorescence (XRF), Particle size analysis, and Fourier transform infrared spectroscopy (FTIR). The researchers also designed and fabricated a prototype activated-sand filter and conducted performance tests on river water. A 2^k factorial design was employed to optimize the filter's effectiveness, focusing on factors such as sand grain size, flow rate, residence time, sand concentration, and loading rate. The results of the study showed that the multi-layered filter design effectively removed a variety of contaminants. Removal efficiencies for various pollutants included 35.1 % and 28.1 % for nitrate, 66.7 % and 39.9 % for lead, 55.6 % and 73.3 % for copper, 77 % and 70.5 % for total iron, and 85.3 % and 86.4 % for turbidity in two different filter cartridges. While there were slight increases in certain water parameters like sulfate, alkalinity, and calcium, these changes remained within acceptable limits according to the Kenya Bureau of Standards and the World Health Organization standards. In conclusion, the silver-activated sand filter system proved to be a viable and cost-effective solution for improving water quality in rural and informal settlements in Kenya. It demonstrated significant pollutant removal and complied with health standards, making it a sustainable option for enhancing water safety and public health in areas where clean water access is a major challenge.

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KEYWORDS

Household, Drinking water, Point of use, Physicochemical contaminants, Cartridge filter, Silver Activated Sand, Charcoal.

INTRODUCTION

Water quality is an essential issue in Kenya, where the acceptable limits are regulated by the Kenya Bureau of Standards [1] and the World Health Organization [2]. The utilization of sand as a filtration medium has long been a fundamental approach in water treatment processes, harnessing the natural ability of sand to remove particulate matter and contaminants from water. However, conventional sand filtration systems have faced limitations in their effectiveness, particularly in addressing emerging water quality challenges [3]. In recent years, the concept of silver-activated sand filtration has emerged as a potential innovation in this field, promising enhanced performance and broader applicability.

Existing filtration technologies, such as screen filters, slow and fast sand filters, diatom filters, and charcoal filters, have been extensively studied and employed in drinking water treatment [4]. The performance of these conventional filtration methods is closely tied to the properties of the filter media, which can significantly impact the filtration process [4]. Efforts to optimize filtration efficiency have led to the exploration of alternative filter media, including the incorporation of silver into the sand filtration system.

The latest research on silver-activated sand filters introduces several novel advancements that redefine the potential of this technology. One key innovation lies in the optimization of silver release mechanisms. Researchers have pioneered controlled-release silver formulations that enhance filter performance while ensuring minimal silver leaching. These formulations utilize cutting-edge nanomaterials and composite coatings, which ensure silver is only released when microbial contamination is detected. This breakthrough retains the filter's antimicrobial activity while preventing unnecessary environmental contamination. Silver's ability to inhibit biofilm formation in filters is a significant advantage over conventional filters. Silver-impregnated filters were far less likely to develop biofilms compared to standard filters, thus maintaining their filtration efficiency over a longer period. Additionally, Silver-activated filters not only remove pathogens but also effectively reduce chemical contaminants, such as pesticides and volatile organic compounds (VOCs).

Another groundbreaking development is the integration of silver with other materials such as activated carbon, biochar, and zeolites, which significantly improve both the durability and efficiency of the filters. These hybrid filters have demonstrated superior performance in removing both microbial and chemical contaminants while also extending the life of the filter without sacrificing its effectiveness. This approach addresses both long-term filter functionality and the challenges of persistent contaminant removal.

Silver uses a multifaceted approach in removing physicochemical contaminants; Silver acts as a catalyst in redox reactions, helping to oxidize organic pollutants (e.g., pesticides, herbicides) and reduce harmful substances like chlorine and chloramine in water. This reduces the toxicity of the contaminants and improves water quality. It also enhances the adsorption capacity of activated carbon filters and helps remove volatile organic compounds (VOCs), pesticides, and heavy metals by reacting with them or precipitating them out of the water. This improves the overall contaminant removal efficiency. Furthermore, it assists in coagulation and flocculation, where contaminants such as suspended particles and colloids aggregate into larger particles (flocs) that can be easily removed. This process helps to eliminate a wide range of pollutants, including suspended solids and some heavy metals.

Sustainability has also been at the forefront of the research, with a clear emphasis on reducing the environmental impact of silver usage. Novel filter designs incorporate silver in smaller quantities, using more sustainable methods such as green synthesis techniques to minimize chemical waste. This not only enhances the eco-friendliness of the filters but also makes their operation more resource-efficient.

Finally, the research utilizes the synergy of silver, sand, zeolite, and activated carbon to develop a robust, innovative design capable of removing harmful particles such as heavy metals, chlorine, volatile organic compounds, and odors while being both cost-efficient and sustainable for widespread deployment, especially in developing regions.

Determining Contaminant Differences Before and After Filtration

Determining the difference in contaminant levels before and after filtration is an essential step in evaluating the performance of any water treatment system, including activated sand-based filters. The effectiveness of such filters is typically assessed by measuring the reduction in contaminants such as turbidity, microbial pathogens, and chemical pollutants. These analyses help to quantify the filter's removal efficiency and establish whether it meets the required water quality standards. Below, we explore the factors influencing the removal of contaminants and the methodologies used to assess these differences.

Turbidity removal and performance evaluation

Turbidity, which is the cloudiness or haziness of a liquid caused by suspended particles such as silt, clay, and organic matter, is one of the most common indicators of water quality. High turbidity levels can reduce the effectiveness of disinfection methods (like chlorine or UV light) and impede the performance of filtration systems by clogging filter media **[5,6]**. Therefore, measuring the reduction in turbidity before and after filtration is critical for evaluating the efficacy of activated sand-based filters.

Activated sand filters are particularly effective at removing suspended solids, and studies have shown that these filters can achieve significant reductions in turbidity. For instance, research by Zhang, **[7]** demonstrated that activated sand filters can reduce turbidity levels by up to 90%, depending on factors such as the filter design, grain size, flow rate, and the characteristics of the water being filtered. A similar study by **[8]** confirmed that turbidity reduction is highly influenced by the media's porosity and surface area, which allows for better particle trapping and sedimentation.

The efficiency of turbidity removal also depends on the nature of the suspended particles. Coarser particles may be removed more effectively by filtration, while finer particles or colloids, which tend to stay suspended in water for longer periods, may be more challenging to remove. Therefore, studies typically consider not just the overall turbidity reduction but also the types of particles removed during filtration **[8]**. In some cases, pre-treatment steps like coagulation or flocculation may be used in combination with activated sand filtration to enhance turbidity removal.

Chemical contaminant removal

While activated sand filters are known for their ability to remove suspended solids and microorganisms, their ability to remove dissolved chemical contaminants, such as heavy metals, pesticides, and organic chemicals, is less straightforward and depends on the specific contaminants involved. Activated sand filtration works primarily through physical adsorption and surface interactions, and the degree to which it can adsorb chemical pollutants is influenced by the surface area and porosity of the sand, as well as the chemical characteristics of the contaminants.

Studies have shown that activated sand can be effective in removing certain chemical pollutants, particularly heavy metals like lead, arsenic, and mercury. For example, a study by Liu et al. **[6]** found that activated sand filters were able to significantly reduce concentrations of lead and arsenic in contaminated water. The removal process is primarily based on adsorption, where the chemical contaminants are attracted to and held on the surface of the sand particles. The efficiency of heavy metal removal depends on several factors, including the pH of the water, the ionic strength, and the presence of other competing ions.

For pesticides and herbicides, the adsorption capacity of activated sand may be less effective, especially for hydrophobic compounds. The objective of this research is to design and evaluate the physicochemical performance of an activated-sand-based Point of Use water treatment system for household applications in rural and informal settlements in Kenya.

MATERIALS AND METHODS

Figure 1 spells out the research framework undertaken in this research

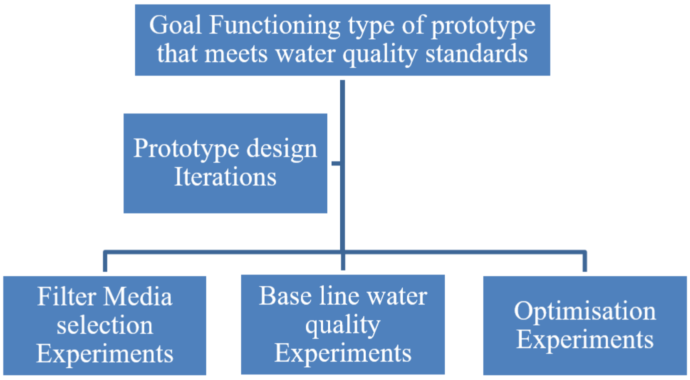


Figure 1. Conceptual model of research and development of prototype

Design of Experiments

In this research, a 2^k factorial design with five control factors (sand grain size, flow rate, residence time and concentration, and loading rate) was employed to optimize the activated sand filter performance in the removal of physicochemical contaminants. The experimental setup consisted of two cartridge configurations. The factors and levels are shown in Table 1.

Table 1. Factors and levels under investigation

Household water treatment Model using Activated Sand
Table of real Values

Factors	**Units**	**High Level**	**Low Level**
Grain size	µm	1180	850
Flow rate	mL/min	37.5	50
Residence time	min	240	180
Sand concentration	g/L	225	180
Loading rate	mg/mL	5x10e10	1x10e10

Coded Parameters

Factors	**Coding**	**Units**	**High level**	**Low level**	**Response**
Grain size	X1	µm	1	-1	
Flow rate	X2	mL/min	1	-1	
Residence time	X3	min	1	-1	
Sand concentration	X4	g/L	1	-1	
Loading rate	X5	CFU/mL	1	-1	

Materials and Chemicals

The activated carbon was sourced from Panthera-activated Carbon$^{\text{TM}}$, Silver activated sand was sourced from Nikken Corporation (Japan), with commercial name Clinca205 and the zeolite was sourced from Rift African gems Kenya. Leaching Test of Silver in Activated Sand: A leaching test will be performed on the sample of activated sand according to Notification No. 45(2000), “Test for materials of mechanical equipment and materials” based on Ministerial Ordinance No 15(2000) Japan, “Technical standards for water Utilities”.

Method

Extraction procedure

The sample will be washed with flowing tap water for 1 h, rinsed with pure water three times, and then washed with leachate (pH 7.0±0.1, hardness 45± 5 mg/L, alkalinity 35± 5 mg/L, residual chlorine 1.0± 0.2 mg/L) three times. Then, the sample was immersed in the leachate and allowed to stand for 24 h at 23 °C. The obtained solution was used as the test water.

In addition, the leachate alone (without sample) was prepared in the same manner as the test water and used as the method blank. The immersion rate was set at 50 g of the sample per 1L of the leachate, and no conditioning was performed.

Experimental techniques

Fourier Transform Infrared (FTIR): The functional groups present in the different filter media were determined using a Jasco FT/IR-6600 type A equipped with a standard light source and a triglycine sulfate (TGS) detector. The spectrum was obtained at a resolution of 4 cm-^{1,} and scans ranged from a wavelength of 400 cm^{-1} to 4000 cm^{-1}.

X-ray Fluorescence (XRF): The elemental composition of the filter media was determined using a Bruker CTX CounterTop XRF, which can analyze up to 48 elements per calibration, with a wide elemental range from Mg to U.

Particle Size Analysis: Preparation of media. The filter media is first washed in clean water thoroughly, then oven-dried at 110 °C for 8 h.

Particle size analysis and grading were done as per the Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM C-136-06 [9], where a sample of dry aggregate of known mass is separated through a series of sieves of progressively smaller openings for determination of particle size distribution.

Procedure.

1. The sample was weighed to the nearest 0.1 g by the total weight of the sample. This weight was used to check for any loss of material after the sample had been graded. Suitable sieve sizes were selected in accordance with the specifications.

2. The sieves were nested in order of decreasing size from top to bottom, as shown in Figure 2. Agitation and shaking of the sample until all the media had settled in different sieve meshes was done.

Figure 2. Nested sieves

3. After the material had been sieved, each tray was removed, each size was weighed, and each weight was recorded to the nearest 0.1 g. Care was taken to remove any aggregate

trapped within the sieve openings by gently working from either or both sides with a trowel or piece of flat metal until the aggregate was freed.

4. Plot the particle distribution curve and Calculate the Uniformity Coefficient
5. The effective size of a given sample is the particle size (in mm), where 10 % of the particles in that sample (by weight) are smaller, while 90 % are larger. Usually, this is denoted as the D10.

The size distribution is represented by the Uniformity Coefficient, which determines how well-graded the sample is. This is done by taking the D60 and dividing it by the D10. For slow sand filtration, some degree of uniformity is desirable in order to ensure that the pore sizes between the grains are reasonably regular and that there is sufficient porosity **[10]**.

Sample Collection and Transport

Sample collection was done according to WHO guideline procedures **[2]** in order to avoid contamination and to ensure accurate results.

Sterilization of sample bottles: Plastic bottles of at least 200 mL capacity with plastic screw caps were cleaned thoroughly and then rinsed with distilled water and sterilized by autoclaving at 121 °C for 15 min. Other materials used in the bacteriological analysis, such as dilution bottles, small cylinders, beakers, tubes, buffer solutions, and pipettes, were also sterilized. Water was sampled from the two selected rivers and the baseline water characteristics of the rivers were performed.

Sampling procedures: Water samples for physicochemical analysis were collected in sterile bottles, which were kept unopened until the time of filling, usually less than 24 h **[2]**. The cork was removed, and the bottle was held by the other hand around the base of the bottle. The researcher ensured that the bottle was not rinsed with the sample during collection and that the bottle was not completely filled to allow for shaking prior to analysis. Surface waters such as rivers were sampled away from the banks as much as possible.

Sampling location: Two sampling points were selected in reference to the objective of the research to provide a point-of-use device for rural and urban informal settlements.

The sampling points are:

1. Kesses River as shown in Figure 3, is a representative of a rural settlement.

   Location: Kesses Sub County, Uasin Gishu County, Kenya;
   Main feature: Kesses Dam, a significant water reservoir;
   Water source: Primarily fed by the Tarakwa and Nderugut rivers;
   Terrain: High altitude plateau within the Rift Valley;
   Usage: Water supply for domestic use, irrigation, and recreational activities;

2. Sosiani River, as shown in Figure 4, represents the urban settlements.

   Source: Kaptagat Forest
   Major Town: Eldoret
   Drainage Basin: Nzoia River basin, which flows into Lake Victoria
   Catchment Area: Primarily agricultural land use

Figure 3. Kesses river site coordinates and sampling points

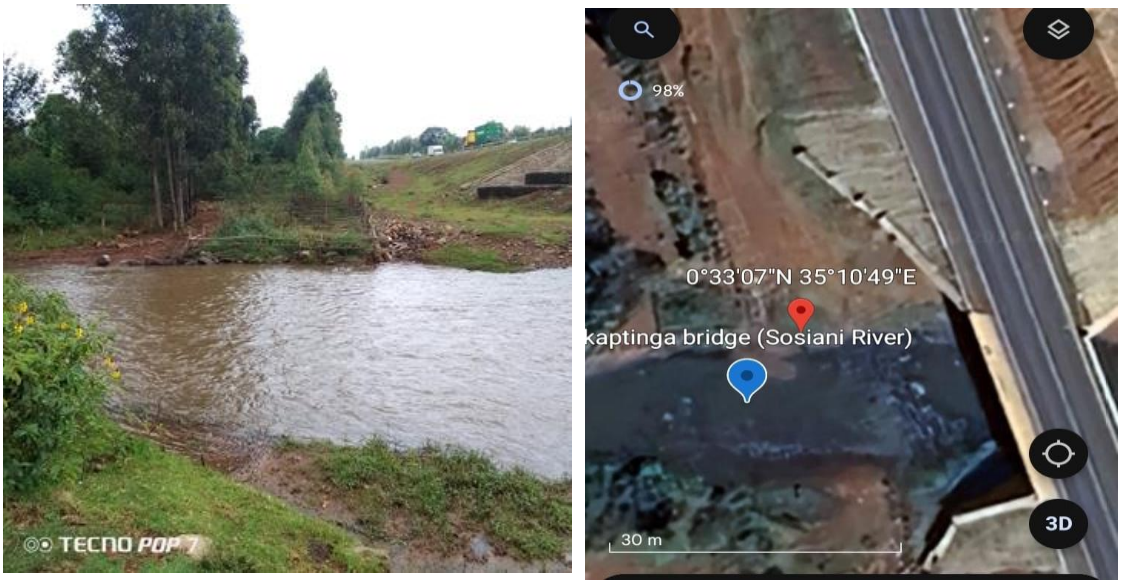


Figure 4. Sosiani river sampling site coordinates

Design of the Activated-sand-based filtration unit

Figure 5 shows the basic design of the point-of-use water treatment prototype developed by the researchers, whereas Figure 6 represents the filter cartridge configurations, which allow for the replacement of spent cartridge media.

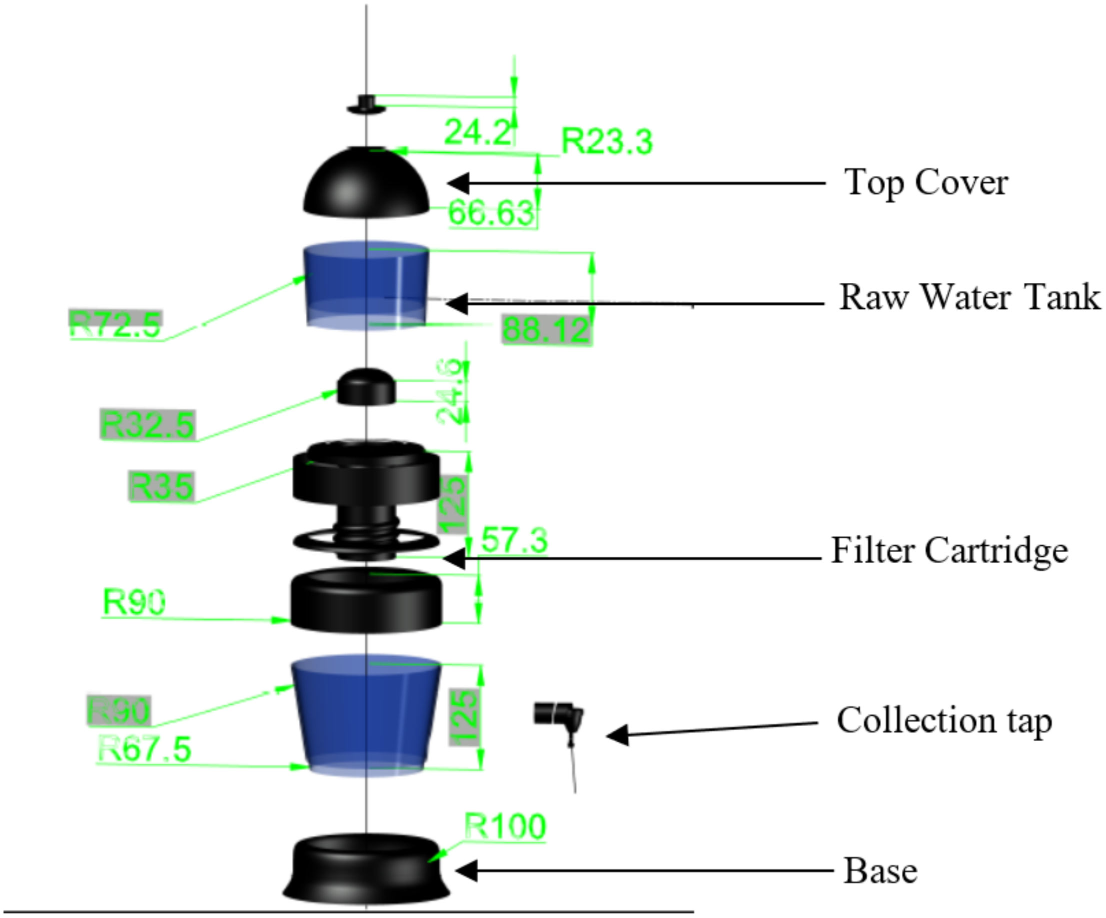


Figure 5. Basic design of activated sand based device

Figure 6. Constructed filter cartridge configurations

Design and Construction of prototype: The fixed bed was designed and constructed to the specifications below:

- Total Bed Height = 120 cm
- Total bed Width = 80 cm

The container volume is calculated according to **Eq.**(1):

$$V = \pi r^2 h = 0.5585 \text{ cm}^3 \tag{1}$$

The flow rate was measured as 29.07 cm^3/s. The Empty Bed Contact Time (EBCT) is calculated according to **Eq.**(2).

$$EBCT = \frac{\{Volume\ of\ media\}}{\{Flow\ rate\}} = \frac{0.5585}{29.07} = 3.2\ min \tag{2}$$

The filter cartridges were packed as shown in Table 2.

Table 2.Proportions of media in fixed bed adsorption column

Layer	Cartridge 1 mass (g)	Cartridge 2 mass (g)
Activated Carbon	97.6	97.6
Zeolite	76.3	76.3
Silver activated Sand (Coarse)	168	
Fine activated charcoal		150
Zeolite	72.7	72.7
Silver activated Sand (Fine)	60	120

RESULTS AND DISCUSSION

XRF Analysis

X-ray Fluorescence (XRF) analysis is an elemental analysis technique used to determine the composition of materials based on their unique fluorescence properties when exposed to X-rays. In the context of assessing filter media for water treatment, XRF can provide crucial information regarding the elemental makeup and potential contaminants present in the media.

The results obtained from XRF analysis of the filter materials are shown in 3 reveals that all the filter materials, contain Silica (SiO_2), Alumina (AI_2O_3), Ferric Oxide (Fe_2O_3), Calcium

Oxide, Phosphorus pentoxide(P_2O_5), Chloride, Potassium Oxide and other oxides. These results compare to those of **[11]** and **[12]**.

Activated sand and river sand show presence of MgO, which has remarkable adsorption capacity. Their unique structural properties and large surface area enable exceptional pollutant removal, including heavy metals, organic compounds, and dyes, from wastewater **[13]**. Additionally, synthesis and functionalization techniques show promise in enhancing adsorption performance and selectivity, offering tailored solutions to specific treatment challenges. Tailoring the surface chemistry and morphology of MgO nanoparticles allows for improved pollutant removal efficiency and paves the way for tailored solutions to specific wastewater treatment challenges **[13]**.

Table 3. XRF analysis of the filter media (g/100 g sample)

Element Name	Activated Sand	R. Sand	Charcoal	Activated Carbon	Zeolite	Mineral Stone
MgO	3.884	5.106	-	-	-	-
AL_2O_3	1.353	6.038	19.569	2.622	20.468	14.388
SiO_2	93.317	84.899	40.857	80.277	69.482	77.667
P_2O_5	0.105	0.162	1.584	1.389	-	0.179
S	0.017	-	0.041	0.11	-	-
Cl	0.055	0.055	0.819	1.51	0.111	0.123
K_2O	0.295	1.839	5.258	2.234	2.997	4.75
CaO	0.124	0.812	15.959	6.791	1.591	1.448
Ti	0.026	0.097	2.603	0.598	0.613	0.158
Cr	0.057	0.018	-	0.146	0.011	0.018
Mn	0.076	0.017	0.555	0.091	0.028	0.026
Fe	0.66	0.797	12.526	4.148	4.403	0.926
Ni	-	-	-	-	0.007	-
Cu	0.005	0.004	0.012	0.066	0.009	0.003
Zn	0.002	-	0.036	-	0.007	0.002
As	-	-	0.001	-	0.001	-
Rb	0.002	0.003	0.01	-	0.018	0.022
Sr	0.002	0.039	0.045	0.017	0.008	0.061
Y	-	0.002	0.01	-	0.007	0.002
Zr	0.001	0.014	0.079	-	0.042	0.018

FTIR analysis

Fourier Transform Infrared Spectroscopy (FTIR) is a valuable analytical technique used to examine the chemical composition and functional groups present in filter media for water treatment. By analyzing materials like activated carbon, sand, and zeolite, FTIR provides insights into their properties, adsorption characteristics, and interactions with contaminants.

To prepare samples for analysis, filter media are typically dried and ground into a fine powder, enhancing the penetration of infrared light for accurate results. The resulting spectra display peaks that correlate to specific molecular vibrations, allowing researchers to identify functional groups such as hydroxyl, carbonyl, and amine. This identification can indicate the presence of pollutants or the condition of the filter media. The recorded spectra for activated charcoal is shown in Figure 7.

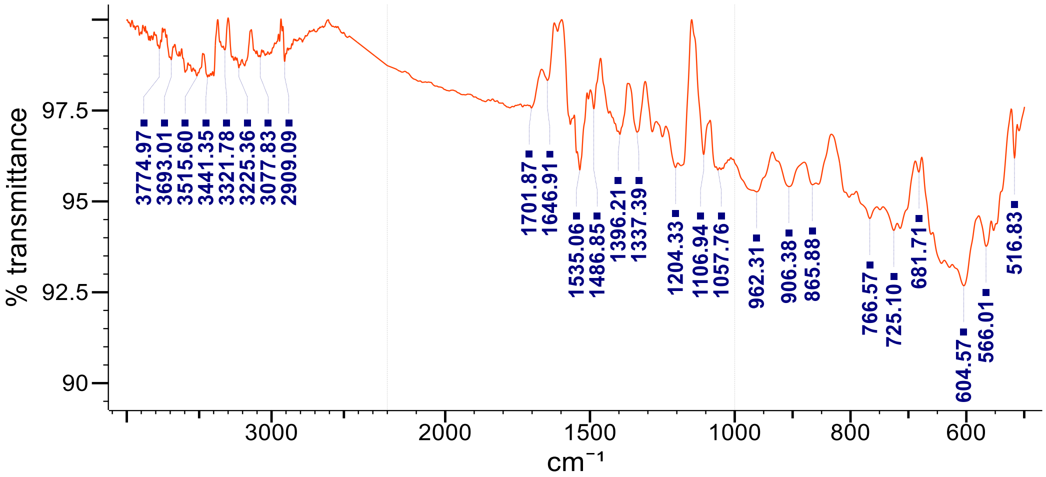


Figure 7. FTIR spectra of activated charcoal

The infrared transmission peaks (Figure 7) recorded at wavelengths 3774.97 cm^{-1} and 3693.01 cm^{-1} exhibited a wide and broad transmission band. Here, the presence of a broad transmission band was attributed to the O-H stretching mode of non-bonded hydrogen hydroxy groups attached to the structure or surface-adsorbed moisture, this is characteristic of phenols **[14]**. The absorption peaks at 3515.60 cm^{-1} is characteristic of Dimeric OH stretch, whereas 3441.35 cm^{-1} allude to a non-polymeric OH stretch. The bands at 1057.76 cm^{-1} and 1106.94 cm^{-1} be assigned to phosphate ions **[15]** which aid in precipitate formation **[16]**, whereas the peaks at 725.10 cm^{-1}, 766.57 cm^{-1} and 865.88 cm^{-1} can be assigned to the Aryl group **[14]**. There is also the presence of amino and organo-halogen groups. With the major bonds being carbon or oxygen based, we can confirm that carbon and oxygen are the main elements in activated charcoal as attributed to in the elemental analysis in 3, confirming its organic nature.

The spectral analysis of activated sand is shown in Figure 8. The infrared transmission peaks recorded at the wavelengths 3603.34 cm^{-1}, 3694.94 cm$^{-1,}$ 3730.62 cm^{-1}and 3820.29 cm^{-1} exhibited strong narrow transmission bands. Here, the presence of a narrow transmission band was attributed to the O-H stretching mode of non-bonded hydrogen hydroxy groups, this is characteristic of phenols **[14]**.

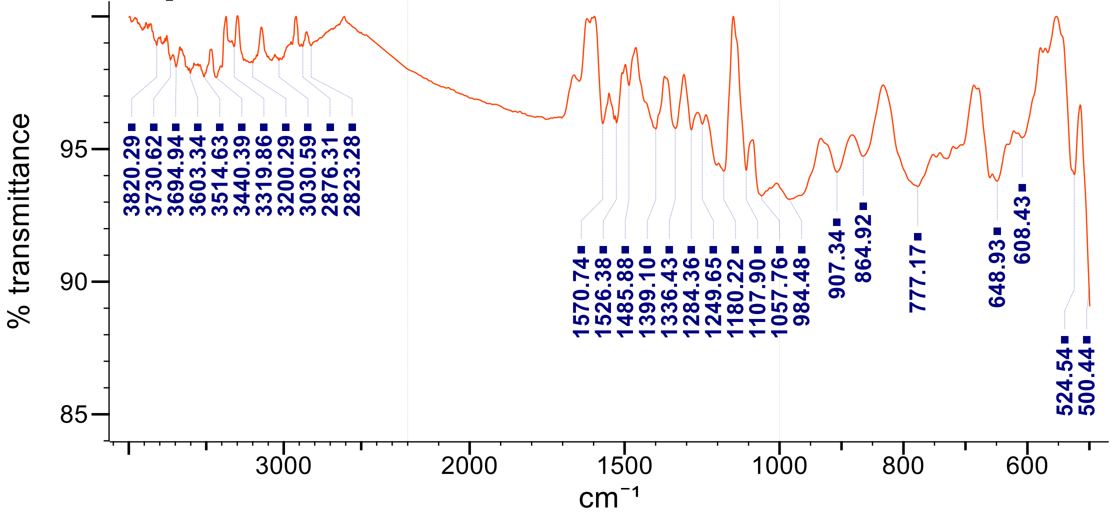


Figure 8. FTIR spectra of activated sand

The absorption peaks at 3514.63 cm^{-1}, 3440.39 cm^{-1}, 3319.86 cm^{-1} and 3200.29 cm^{-1}, are attributed to H-bonded with an OH stretch hydroxy group. The strong peaks at 2876.31 cm^{-1} and 2823.28 cm^{-1} are characteristic of Carboxylic acid **[17]** groups. The peaks at 1526.36 cm^{-1} and 1570.74 cm^{-1} are indicated for aromatic ring stretch of C=C-C bond typical of methylene. The band peaks of 1107.90 cm^{-1} and 1180.22 cm^{-1} are assigned to phosphate ions **[15]** which aid in precipitate formation [16], whereas the peaks at 984.48 cm^{-1} and 1057.76 cm^{-1} is indicative of silicate ions [18]. Transmission at 1249.65 cm^{-1} is indicative of aromatic phosphates group. There is also the presence of alkenes, amino, aryl and organo-halogen groups.

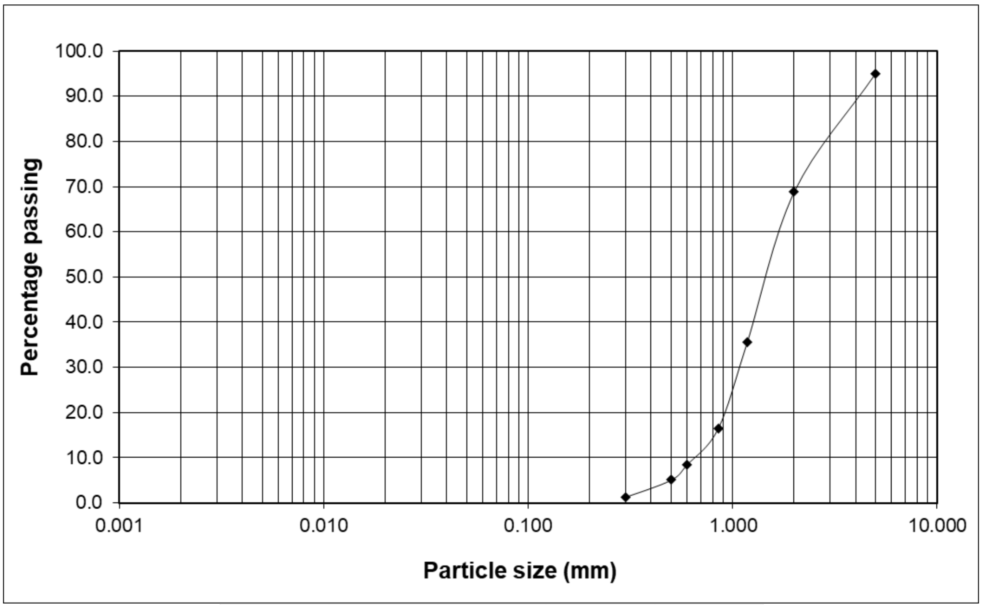
The existence of phosphate and silicate ions in the activated sand, we can confirm that silica, aluminum oxide, magnesium oxide and Potassium dioxide are the main elements in activated sand as attributed to in the elemental analysis in Table 3, thus confirming its inorganic nature.

Particle size analysis

The sand particle analysis is listed in Table 4. The uniformity factor obtained is 1.83 which is less than the recommended factor for slow sand filtration which is 2 [19]. The sand particles were categorized into two regimes: fine sand particles with mesh size of less than 500 µm and Coarse sand between 500 and 1500 µm.

Table 4. Sieve analysis

Sieve (mm)	Mass (kg)	% Retained	% Passing
5.000	0.380	5.0	95.0
2.000	1.980	26.2	68.8
1.180	2.510	33.2	35.6
0.850	1.450	19.2	16.5
0.600	0.600	7.9	8.5
0.500	0.260	3.4	5.1
0.300	0.285	3.8	1.3
Pan	0.100	1.3	
Total Mass (kg) = 7.565			



D_{10} = 0.6 mm
D_{60} = 1.1 mm
C_u = **1.83**

Figure 9 . Sand particle analysis

Physico-chemical contaminant removal

The following section describes the removal of physicochemical contaminants from filter cartridges 1 and 2. The coding is as shown below:

- KRW 1 – Kesses river water from sampling point 1
- KRW 1.1 – Kesses river water effluent from cartridge 1
- KRW 1.2 – Kesses river water effluent from cartridge 2
- SRW 1 – Sosiani river water from sampling point 1
- SRW 1.1 – Sosiani river water effluent from cartridge 1
- SRW 1.2 – Sosiani river water effluent from cartridge 2
- BRW 1 – Boundary river water on sosiani river
- BRW 1.1 - Boundary river water effluent from cartridge 1
- BRW 1.2 – Boundary river water effluent from cartridge 2

Turbidity reduction in the cartridge filter

The experimental data on turbidity reduction (Figure 10), shows an average turbidity reduction of 85.3 % and 86.4 % on cartridges 1 and 2 on Kesses river water point 1, 91.2 % and 85.9 % on Kesses river water point 2, 80 % and 75.1 % on Sosiani River water and 88 % and 83.2 % on Boundary River water. Overall Cartridge 1 performed better than cartridge 2 in all the sampled waters, this is attributed to the higher volume of silica in the cartridge. These results are supported by those of Fitriani et al. **[20]** who managed removal efficiencies of up to 94.34 % and Das et al. who reported average removal efficiency of 79.96 % **[21]**.

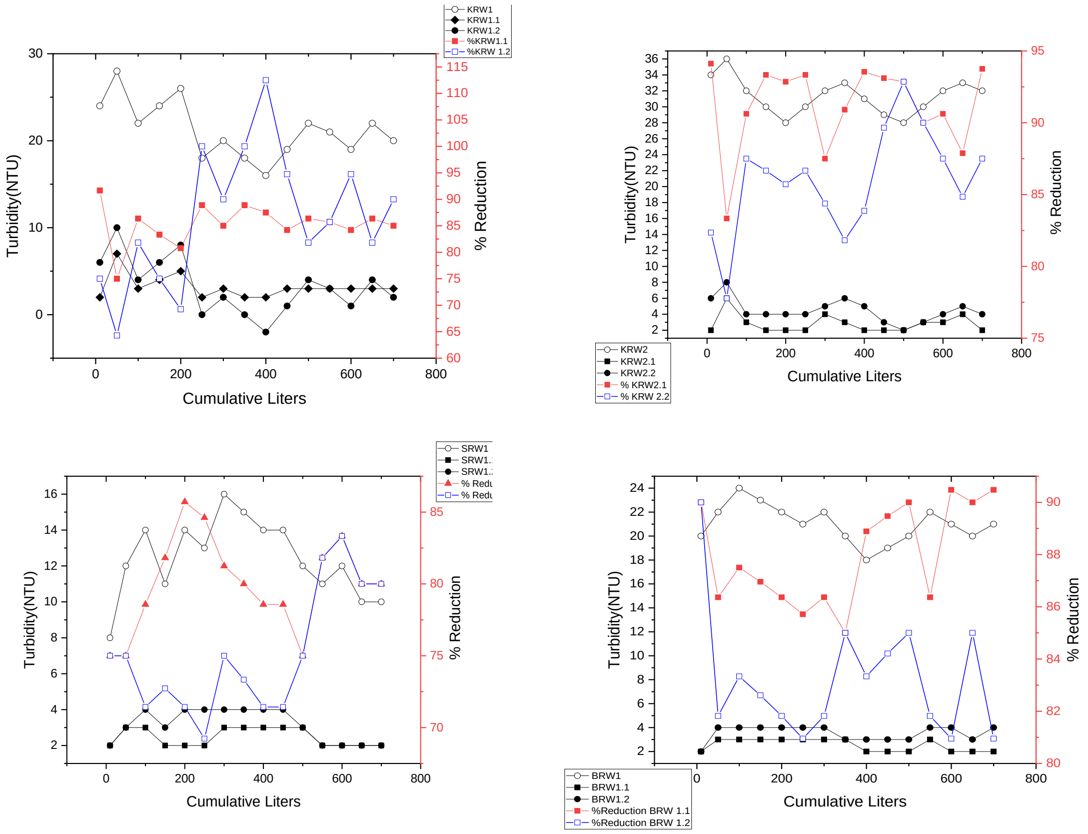


Figure 10. Turbidity removal efficiency

Turbidity was caused by suspended and insoluble species which were removed by both filters efficiently to less than 5 NTU. However, it is noteworthy that any turbidity above 20 NTU, the sample was first pretreated in a bio-charcoal sand system. The main mechanism of turbidity removal by the filter cartridges was surface straining by sand particles as well as other processes such as interception, sedimentation and adsorption [22,23].

Removal of Total Iron in the cartridge filter:

The average iron removal rate was 77 % and 70.5 % in cartridges 1 and 2 respectively (see Figure 11) while running on Kesses water, and 79.2 % and 69.8 % on Sosiani river water. These results are supported by those of Eniola and Sizirici [24], who reported 60.18 and 78.94 % reduction in iron. Other studies have reported 95.28 % reduction in iron [25], 97.9-99.9 % [26], Fitriani et al. who reported removal rates of 45.4-50 % [20] and Endang reported 96.39 % effectiveness.

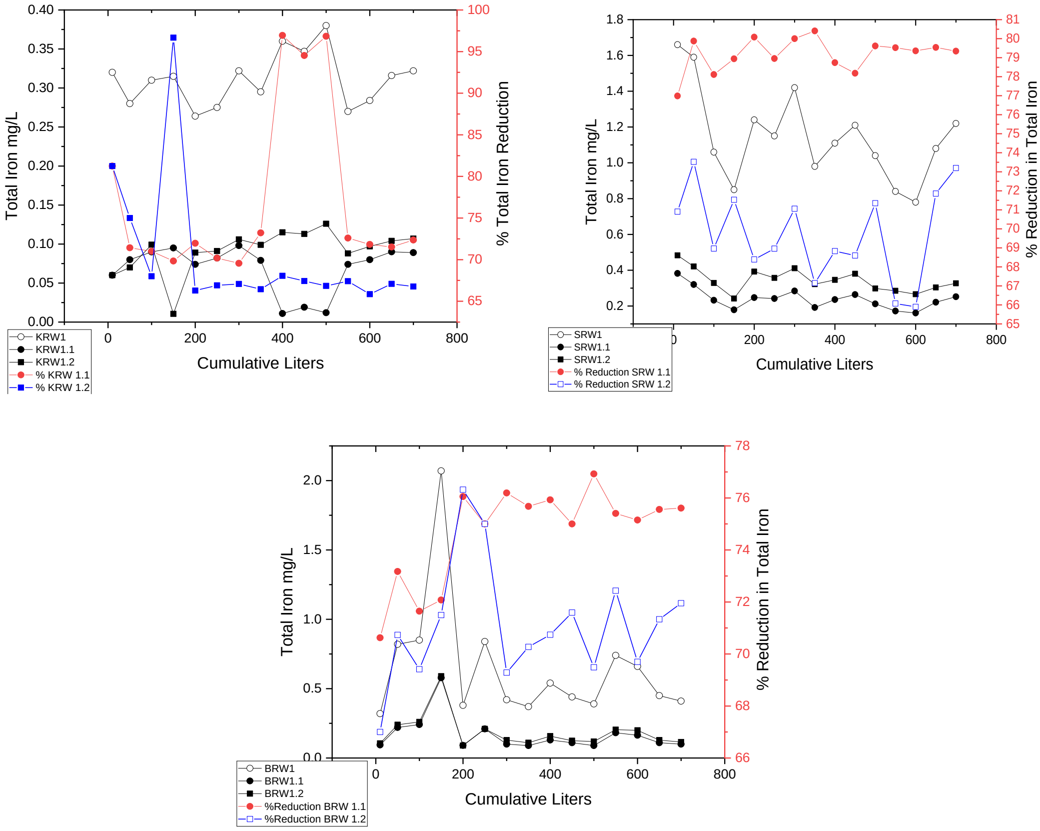


Figure 11. Total iron removal efficiency

This research agrees with the observations of Hidayatullah, that a filter with a silica sand height of 75 cm can achieve an iron parameter removal of up to 72.96 % [27]. The silica sand in the Slow Sand Filter functions as an adsorbent and oxidizing agent for water pollutants. Silica sand has a (-) charge, so that it can attract positively charged particles such as cations from the trapped iron molecules [27].

The efficiency of iron removal was caused by the filter media that can work with ion exchange processes to reduce iron in water. Ion exchange process occurs because of two things, namely there are natural particles such as shells and there are synthetic particles, i.e., organic resins. In research, the ion exchange process occurs because there are natural particles. According to [20], the absorption mechanism of the Fe^{2+} metal ions can occur if it interacts with $CaCO_3$. This was supported because the ionic radii of Fe^{2+} and Ca^{2+} atoms are similar so that they were able to replace the position of the ions. The cycles that occur in the process are as follows:

$$CaCO_3 \rightarrow CO_3^{2-} + Ca^{2+} \qquad (3)$$

$$CaCO_3(s) + Fe^{2+} + CO_3^{2-} \rightarrow FeCO_3 + Ca^{2+} \quad (4)$$

$$Fe^{2+} + CO_3^{2-} \rightarrow FeCO_3(s) \quad (5)$$

The insoluble Fe metal will be retained in the pores of the filter media when water passes through the media, so that it can reduce the Fe content in the water as it exits the outlet **[27]**. In addition, iron removal was influenced by the transport mechanism so that an adsorption process occurs in the filtration unit. The adsorption process occurs because there is a diffusion process so that the adsorbate is adsorbed. In addition, there is an attachment mechanism caused by the van der Waals force **[28]**. Silica sand have a negative (-) charge, so they can attract positively (+) charged particles such as cations from iron molecules **[20]**.

Variation of Calcium in the cartridge filter

The graphs in Figure 12 show the variation of calcium between the influent waters and effluent. There was an average increase in Calcium of 7.7 % and 6.9 % in cartridges 1 and 2 while running on Kesses water and 57.4 % and 43.4 % respectively on Sosiani river water. These figures are supported by the study by Sabogal et al. who reported increased levels of Calcium caused by leaching of the elements in the filtration media into the effluent water **[29]**.

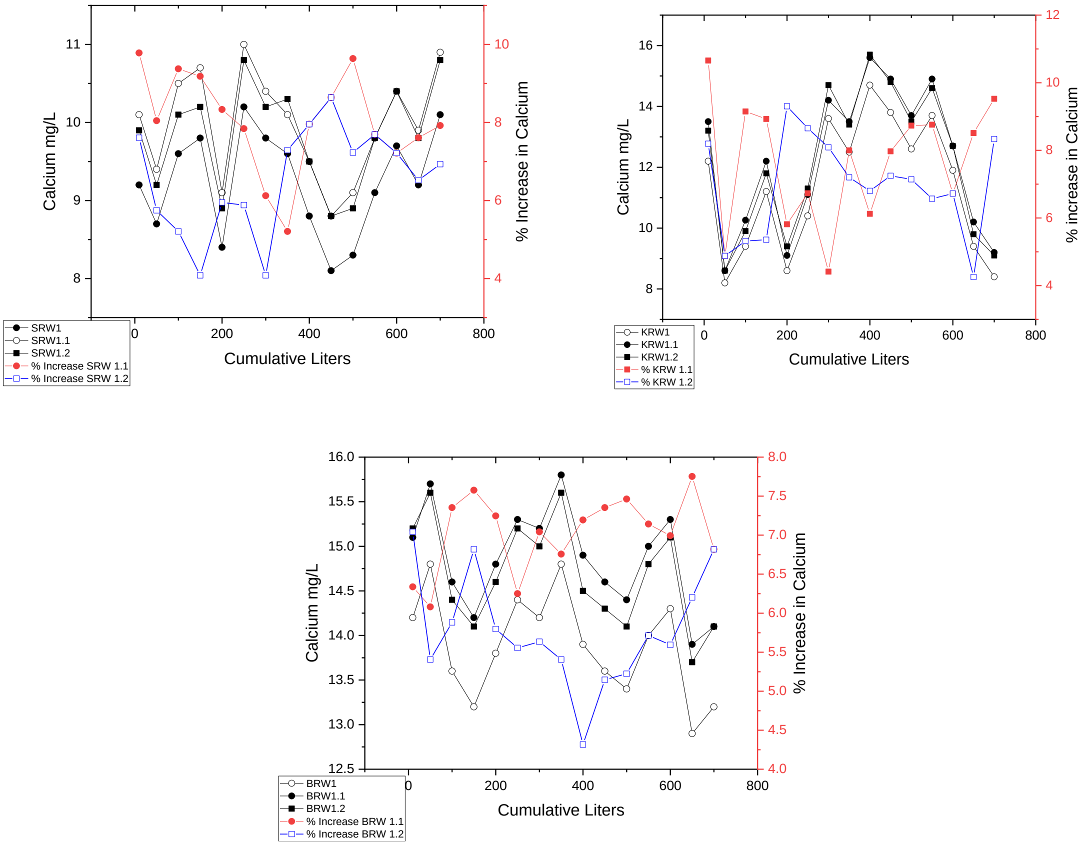


Figure 12. Calcium variation

Variation of Alkalinity in the cartridge filter

The graphs in Figure 13 show that there was an average increase in alkalinity of 7.7 % and 6.9 % in cartridge 1 and 2 respectively running on Kesses water, and 26.1 % and 35.9 % in Sosiani river water. These results are corroborated by those of Ahmed et al. who showed increase in alkalinity for all the filtrates **[30]**.

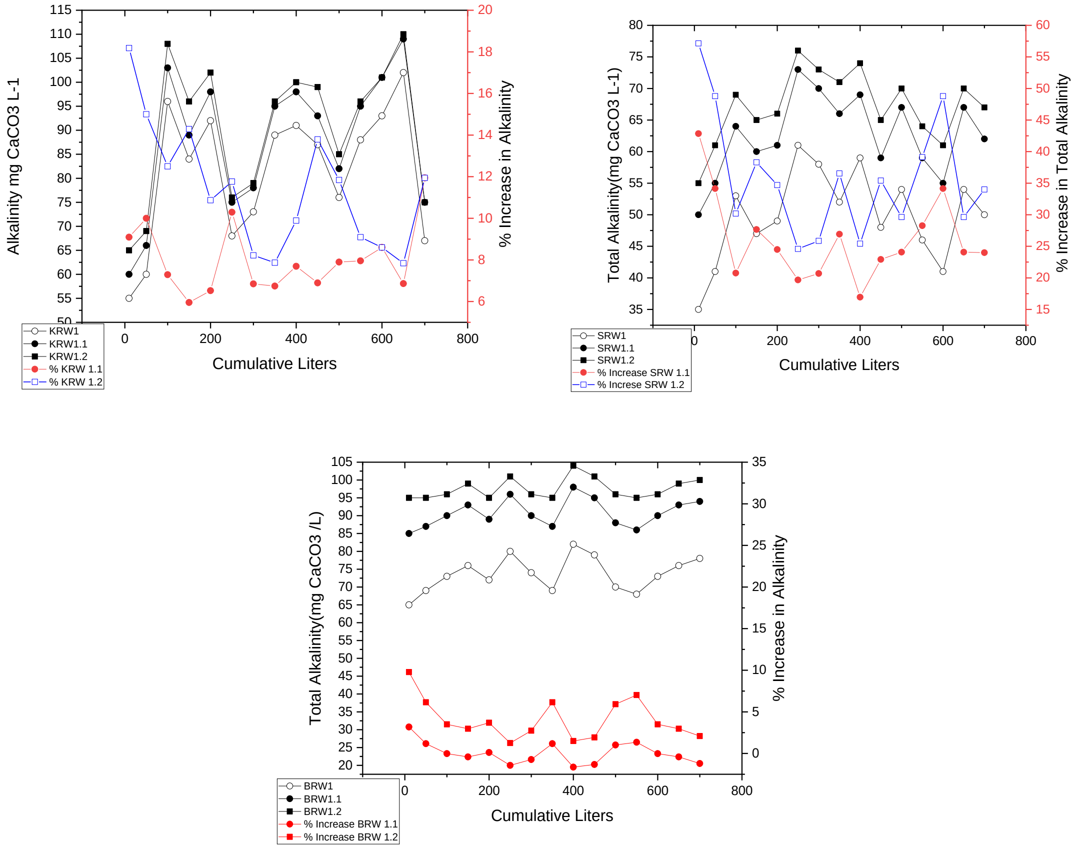


Figure 13. Variation of alkalinity

Removal of Chlorides in the cartridge filter

The graphs in Figure 14 show the removal efficiency of Chloride by the Cartridge filters in different water sources. The average removal efficiency is 7.8 % and 5.2 % in cartridges 1 and 2 while running on Kesses water and 38.9 % and 34.3 % when running on Sosiani river water. Overall Cartridge 1 has better removal efficiency. These results are supported by a study by Ahmed, et al who reported a removal efficiency of 13 % **[30]**.

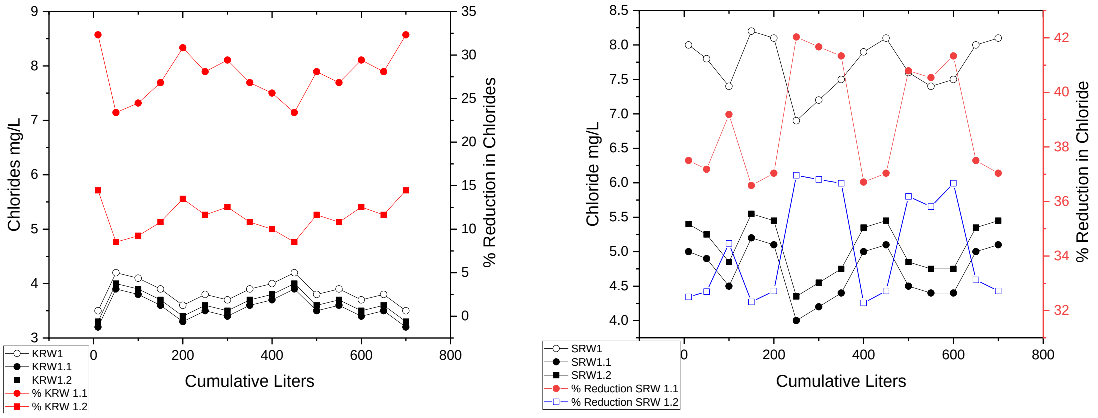


Figure 14. Removal of chlorides

Removal of Fluorides in the cartridge filter

Fluoride removal efficiency was 6.5 % and 5.4 % for cartridge 1 and 2 respectively, while running Kesses river water and 7.7 % and 2.8 % while running Sosiani river water as shown in Figure 15. Overall Cartridge 1 was more efficient at Fluoride removal. These figures are comparatively lower with those of Madhusha et al who in their study reported efficiencies of up to 45 % [31].

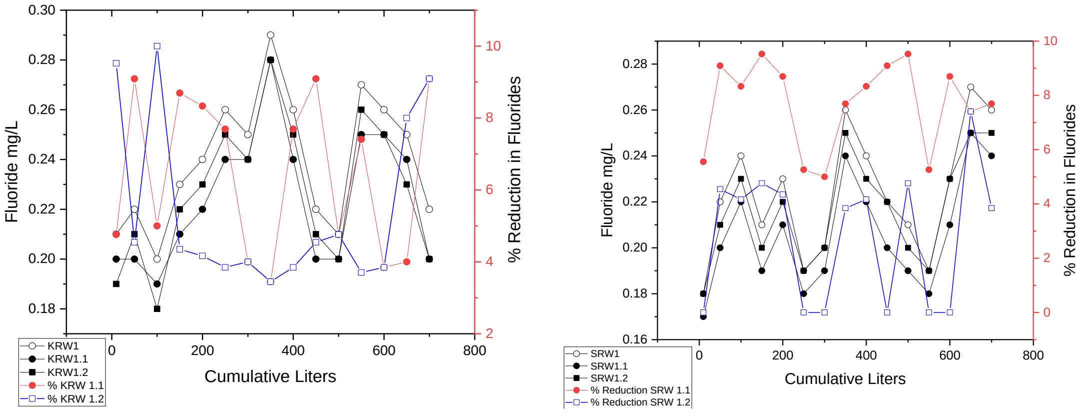


Figure 15. Removal of fluorides

The presence of carboxyl and hydroxyl groups on the surface of the activated carbon influences the material's adsorption characteristics. The location and number of functional groups on the pore structure of activated carbon play a significant role in the adsorption process [32]. Additionally, activated carbon can adsorb anions such as fluoride ions depending on the surface chemistry of activated carbon along with its well-developed porosity, in particular, the presence of OH and phosphate groups leads to such favorable interactions with fluoride.

Variation of Sulphates in the cartridge filter

There was an average increase of 59.5 % and 77.7 % in sulphates for cartridge 1 and 2 respectively running on Kesses water and 19.5 % and 21.3 % on Sosiani river as shown in Figure 16. The increase in sulphate is due to formation of sodium, potassium and magnesium sulphates as the water is filtered through the filter media. In a Study be Fernando et al the average sulfate before modernization was 3.02 mg/L and after the changes it was 17.85 mg/L, almost 500 % increase, due to aluminum sulfate, which leaves a residual sulfate in the water [33]. A similar study by Ohmaid, also showed increased levels of sulphates in product water after filtration [34] This confirms that there are some impurities like sulphates, that cannot be effectively removed by the developed system [35].

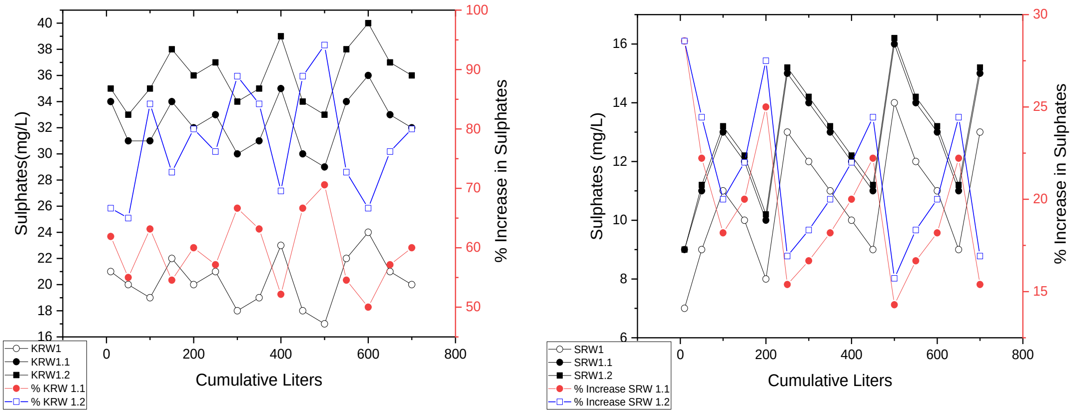


Figure 16. Sulphate removal

Removal of Phosphates in the cartridge filter: The average Phosphate removal was 39.2 % and 34 % in cartridge 1 and 2 on Kesses river water and 12.2 % and 9.4 % on Sosiani river water as shown in Figure 17. The performance of Cartridge 1 was better than that of cartridge

2. These results are supported by the research by De Rozari who obtained removal efficiencies of between 35.9 % and 44.2 % [36].

The presence of Magnesium in the form of Magnesium oxide in the activated sand significantly promotes the adsorption capacity of phosphates due to the strong di-valent cation bridging between Mg and P [37]. The formation of magnesium and calcium phosphates on activated carbon surfaces is considered the primary mechanism of Phosphate removal from water [38].

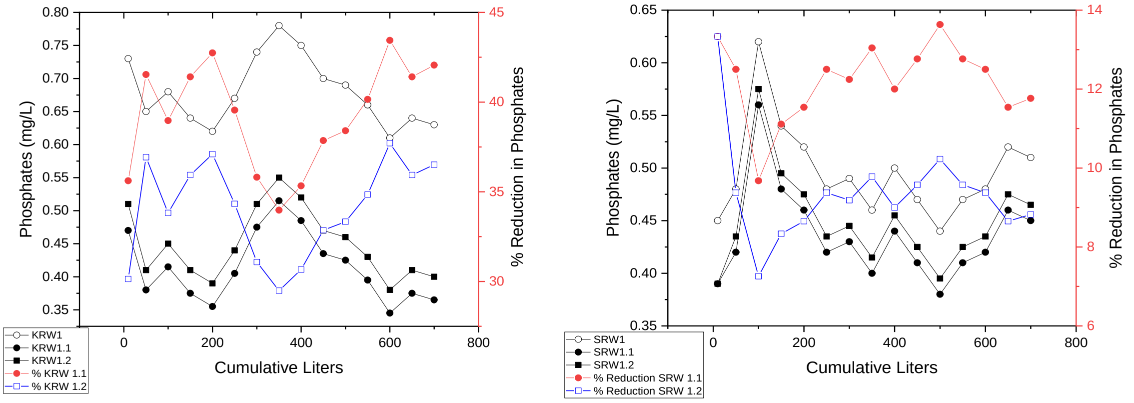


Figure 17. Phosphate removal

Optimized Design

Optimization

Optimization analysis was carried out in Design Expert 13 software and the results are shown in Figure 18. The constraints set for optimization are shown in Table 5. The aim of the optimization is to:

- Maximize flow rates to ensure sufficient quantity of water for household consumption
- Minimize residence time
- Minimize turbidity

This was done while ensuring all the other parameters are within range.

Table 5.Optimization constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Grain Size (µm)	is in range	850	1180	1	1	3
B: Flow Rate(mL/s)	maximize	37.5	50	1	1	3
C: Residence Time (s)	minimize	180	240	1	1	3
D: Sand Concentration (mg/L)	is in range	20	30	1	1	3
E: Loading Rate (cfu/100 mL)	is in range	0	2420	1	1	3
Turbidity (NTU)	minimize	2	6	1	1	3
Iron (mg/L)	none	0.01	0.08	1	1	3
Calcium (mg/L)	none	4.6	13.6	1	1	3
Hardness (mg/L)	none	20	105	1	1	3
Chloride (mg/L)	none	4.5	10	1	1	3
Fluoride (mg/L)	none	0	0.2	1	1	3
Sulphates (mg/L)	none	9	35	1	1	3
Phosphates (mg/L)	none	0.31	0.51	1	1	3

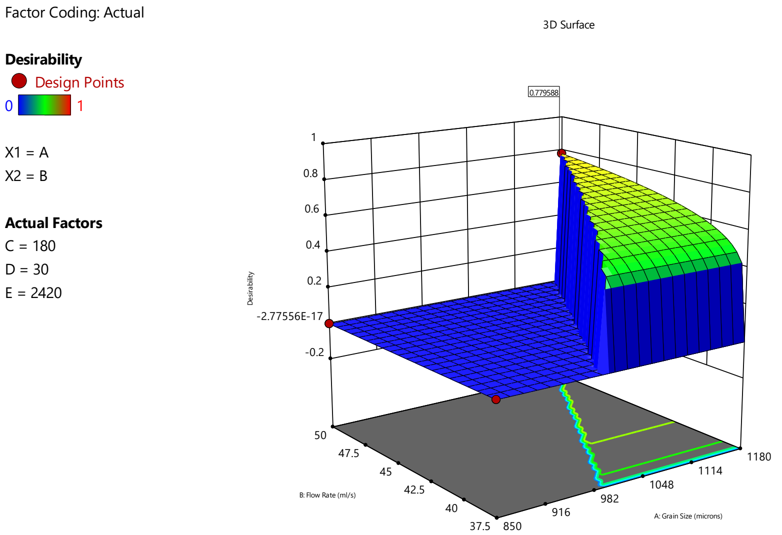


Figure 18. Selected optimized solution in 3D surface

A Point Prediction has been calculated for a Two-sided confidence level = 95%, and population = 99% (Table 6).

Table 6. Point prediction

Analysis	**Predicted Mean**	**Std Dev**	**SE Mean**	**95 % CI low for Mean**	**95 % CI high for Mean**	**95 % TI low for 99 % Pop**	**95 % TI high for 99 % Pop**
Turbidity (NTU)	3.8125	1.94989	0.436009	2.89648	4.72852	-3.89735	11.5223
Iron (mg/L)	0.05875	0.015	0.003354	0.0517033	0.065797	-0.00055976	0.11806
Calcium (mg/L)	8.11875	3.26132	0.729254	6.58665	9.65085	-4.77646	21.014
Hardness (mg/L)	72.625	21.8184	4.87874	62.3752	82.8748	-13.6445	158.895
Chloride (mg/L)	7.31125	1.82666	0.408453	6.45312	8.16938	0.0886771	14.5338
Fluoride (mg/L)	0.091875	0.0913612	0.020429	0.0489553	0.134795	-0.269366	0.453116
Sulphates (mg/L)	27.125	9.24587	2.06744	22.7815	31.4685	-9.43302	63.683
Phosphates	0.42625	0.0726674	0.01625	0.392112	0.460388	0.138924	0.713576
Silver (mg/L)	0.010313	0.0131068	0.002931	0.0041552	0.01647	-0.0415116	0.0621366

From the predicted solution of the optimized solution with design specifications; residence time of 180 min, sand concentration of 30 g/L, Loading rate of 2420 cfu/100 mL, flow rate 50 mL/min, and grain size of 1175 µm, all parameters are within range as per the drinking water standards [1,2].

4. CONCLUSION

The aim of this research was to develop and evaluate the physicochemical performance of an activated sand based point of use household water treatment system. This involved several prototype iterations on the basis of filter media selection, and quantities. Baseline quality water parameters were undertaken and finally an optimization was carried out to identify the most optimal design.

Through XRF analysis the filter media was confirmed to contain Silver, MgO, SiO_2, Al_2O_3 and Copper which are essential elements in water purification. FTIR analysis identified the chemical functional groups present on the surface of filter media. These functional groups, such as hydroxyl, carbonyl, amino groups and carboxyl groups, play a crucial role in the adsorption of specific contaminants i.e., they interact with heavy metals, organic compounds and microorganisms. The particle size analysis, utilizing the coefficient of uniformity resulted in a well-graded filter containing a mixture of different-sized particles working together to improve the removal of a wide range of contaminants. Smaller particles fill the voids between larger grains, creating a more compact structure that improves the efficiency of the filtration process.

The prototype design iterations came up with a multi-layer bed consisting of five layers of filter media packed to facilitate contaminant removal at each layer, at a designed flow rate, loading rate, residence time, and concentration. The final optimum design specifications were a residence time of 180 min, sand concentration of 30 g/L, loading rate of 2420 cfu/100 mL, flow rate of 50 mL/min, and grain size of 1175 µm.

From the study, the physicochemical removal efficiencies are: for nitrates 35.1 % and 28.1 %, Lead 66.7 % ,39.9 %, Copper 55.6 %, 73.3 %, Phosphates 12.2 %, 9.4 %, Fluoride 6.5 %, 5.5 % Chlorides 7.8 %, 5.2 %, Total Iron 77 %, 70.5 % and Turbidity 85.3 %, 86.4 % for cartridge 1 and 2 respectively. It is notable, however, that there was an increase in Sulphates of 59.5 %, 77.7 %, Alkalinity 7.7 %, 6.9 %, Calcium 7.7 %, and 6.9 % in cartridges 1 and 2, respectively. This increase was, however, within the acceptable limits of drinking water standards as per the Kenyan Standards and World Health Organization standards.

The silver-activated sand zeolite carbon water filter is a highly effective and advanced solution for water purification, integrating multiple filtration technologies to address a wide range of water contaminants. The synergy of silver, sand, zeolite, and activated carbon creates a robust system capable of removing harmful particles such as heavy metals, chlorine, volatile organic compounds, bacteria, viruses, and odors. Silver serves a crucial role in providing antimicrobial properties, preventing the growth of bacteria within the filter and contributing to long-term water safety. The zeolite enhances ion exchange, further removing unwanted ions and softening the water, while activated carbon effectively adsorbs impurities that affect water taste and quality. This combination ensures that the silver-activated sand zeolite carbon filter delivers not only clean but also safe and aesthetically improved drinking water, making it a valuable tool for households and communities.

The multi-layered filtration process offers a sustainable, cost-efficient solution to a range of water contamination challenges, making it an excellent option for both domestic and commercial water treatment. As demand for cleaner water increases globally, this filter type stands out due to its ability to address both common and emerging water quality concerns, contributing to better health and environmental sustainability.

Conflicts of Interest

There are no conflicts to declare.

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