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Vertical-horizontal flow roughing filter for improving water quality in sustainable water supply infrastructure

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ABSTRACT

Water is fundamental to cooking, bathing and hygiene, and essentially for life itself. Across many areas, communities rely on bore well water as a source of raw water for domestic needs. Yet this resulting water is mostly not of an appropriate quality, as it has a high iron content and hardness. This study evaluates the performance of a combined vertical-flow and horizontal-flow roughing filter (VRF and HRF) system for bore well water treatment. The system was tested using various alternative filter media, including coconut fiber, silica sand, activated carbon, zeolite, pumice stone, and volcanic black sand, arranged in different configurations. The vertical-flow unit used a media depth of 6 cm, while the horizontal-flow unit used a depth of 15 cm. The results showed that all configurations effectively improved water quality and met standard requirements. The highest performing model, consisting of volcanic black sand, activated carbon, zeolite, and silica sand, achieved a 97.5% reduction in iron and a 13.2% reduction in hardness. These findings indicate that optimized roughing filter systems offer a low-cost and efficient solution for decentralized water treatment.

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1. INTRODUCTION

Clean water is one of the basic resources for various human activities such as drinking, cooking, bathing and washing, sanitation and economic, and social development. With the global population projected to increase significantly, this means that clean water is being demanded at an accelerating rate, and it is increasingly stretching both the availability of water resources and quality in areas where urban environments tend to be quite populous. Water resources are essential for social and economic development. Hence, sustainable water management is equally important for catering to the needs of the present while protecting those of future generations [1]. These concerns are directly tied to sustainable development goal (SDG) 6, which calls for universal access to safe drinking water, improved water quality, and sustainable water management. Many developing communities around the world, as well as developed ones, still rely on groundwater for their daily needs, but such water sources are often not up to drinking water quality standards. Water is abundant but polluted in some areas; clean but lacking in volume in others. Spatial and temporal water quality-based consideration is critical for emphasizing the need for affordable and reliable treatment technologies to improve water quality so that local sources of supply provide safe, usable water.

Interestingly, bore well water is a widely used source of water for many rural and urban areas. That is due to the hardness of bore well water, which often has high iron concentrations and occasionally elevated water hardness. In some rural and urban areas, bore well water is a usual supply of water. Bore wells hardness of water he comes. often has increased iron concentrations and occasionally high-water hardness. Often has high iron levels and occasionally high-water hardness. One of the two parameters that influences it is consumption potential. However, iron contamination refers to the corrosion process of cast iron or steel pipes and natural minerals leaching from alluvial aquifers, which may often cause discoloration and metallic taste [2]–[4]. Dissolved oxygen (DO), chemical oxygen demand (COD), and oxidation–reduction potential (ORP) strongly influence its solubility [4], [5]. Conversely, bore well water hardness is essentially due to dissolved calcium and magnesium ions, which mostly come from the weathering of sedimentary rocks [6], [7]. Other divalent ions like manganese, iron, and zinc can also lead to hardness, but in lower concentrations [6]. The combinations of high iron and hardness levels create a variety of operational and aesthetic issues, including scaling in pipes and appliances, decreased soap efficacy, growth of biofilms, and increased potential for iron-bacteria proliferation [8], [9]. Filtration systems for effective treatment must be sufficiently capable of removing dissolved iron and hardness-forming ions simultaneously.

To tackle these challenges, a variety of passive and low-energy filtration technologies have emerged, providing decentralized treatment solutions appropriate for regions with poor infrastructure. Among them, conventional roughing filters, biochar-based filters, and gravity-driven membrane (GDM) systems are often reported as inexpensive technology which is simple to operate as well as effective for enhancing the quality of water. Specifically, roughing filters are popularly employed as pre-treatment units on account of their proficiency in eliminating suspended solids, for instance [10]–[12], turbidity, organic matter, iron, and nutrients through physical processes such as sedimentation, screening, and interception [13], [14]. They are relevant in biochemical enhancement, such as nitrification and denitrification processes, according to some findings [15]. Contributing to a further improvement of water quality. Due to biochar's high surface area and porosity, biochar-based filters also emerged as a promising innovation. The reported removal efficiencies for metals like Ni^{2+}, calcium (Ca^{2+}), Cu^{2+}, and Pb^{2+} range from 0%–30% while the bacteria *E. coli* shows a removal efficiency of up to 72%–93%, rendering them an attractive option for both physical [16] as well as biological treatment link text. GDM systems represent a technology merging into passive treatment systems based on hydrostatic pressure only, using no chemicals or external power supply, and hence have the highest potential for rural use. Previous studies have reported roughing filter performance, including 90% turbidity removal [13], [17], [18], 85% suspended solid removal, 57% manganese removal, 42% dissolved iron, and up to 38% coliform reduction [19]. Together, these advances punctuate the promise of passive filtration as sustainable, low-cost, decentralized water treatment solutions.

The biochar filters have attracted considerable attention because of their higher adsorption capacity, cost efficiency, as well as stimulating the biological activities in media; reported removal efficiencies ranged 0%–30% for metals like Ni^{2+}, Ca^{2+}, Cu^{2+}, and Pb^{2+} and 72%–93% for *E. coli* [16]. GDM systems are another promising innovation, utilizing membrane-based treatment only requiring hydrostatic pressure, making them suitable for off-grid and low-maintenance applications. GDM systems are another promising innovation, utilizing membrane-based treatment only requiring hydrostatic pressure, making them suitable for off-grid and low-maintenance applications. For similar reasons, due to their simplicity and robustness, some common roughing filters are still being used. This removes turbidity, iron, and manganese, as well as coliforms, effectively, without adding any chemicals. These advancements underscore the multifaceted advantages inherent in passive filtration technologies, encompassing biochar for contaminant adsorption, GDM systems facilitating energy-free membrane treatment, and roughing filters designed for the removal of high turbidity and metal contaminants. Consequently, this emphasizes the critical need to identify context-specific solutions, particularly given the escalating global demand for secure and dependable drinking water sources.

In this larger technology context, vertical-flow roughing filters (VRF) and horizontal-flow roughing filters (HRF) rank among the most practical, commonly implemented configurations for low-cost water treatment technologies. One type of treatment utilizing submerged layered media at VRFs operated through either upflow or downflow mode [20] minimizes clogging and maintenance needs [21]. In contrast, HRFs depend on the lateral flow through gravel layers and achieve a good effect in reducing suspended solids and turbidity from grey water [22], stormwater [23], and surface water [17], [24]. Studies indicate HRFs diminish turbidity many-fold even for highly turbid influent and perform well in urban runoff conditions. When comparing the two systems, HRFs are usually regarded as superior in reducing suspended solids, turbidity, and color, while VRFs tend to provide better oxidation conditions and more stable flow. Although media type, grain size, and hydraulic loading rate (HLR) strongly affect filter performance, the efficiency of both roughing filter systems is ultimately determined by the configuration and arrangement of the filter media. However, very limited research papers studying the optimal arrangement of specialized media (e.g., zeolite, activated carbon, pumice, and volcanic sand) packing in a mixed VRF–HRF system for possible simultaneous removal of iron and water hardness. It indicates a significant research gap because the media configuration directly affects contact time, adsorption behavior, aeration, microbial activity, and overall treatment efficiency.

To fill this gap, the current work develops and assesses a combined VRF–HRF system for synergistic, multi-stage treatment. The VRF component provides aeration and oxidation of dissolved iron, and the HRF component increases filtration contact time and removal of fine particles and dissolved ions. This combined configuration is of particular concern for the region, such as Dusun Ngandat, Mojorejo Village, Batu City, where people complain about yellowish groundwater with a metallic taste that implies significant iron and hardness levels beyond the national drinking water quality standards. In this study, several configurations of inexpensive filter media—coconut fiber, activated carbon, zeolite, pumice stone, silica sand, and volcanic black are tested to identify the most effective combination for iron and hardness removal. This study aims at discovering an optimized, economic, easy-to-implement filtration design incorporated with bore wells for rural communities of the nation, rather than only for households, by evaluating different media combinations through comparison against drinking water norms set up by the Ministry of Health Republic Indonesia [25].

This study's key contribution to the field evaluates how specific combinations and placements of specialized filter media impact VRF–HRF system performance, an area where published literature is lacking. The targeted media arrangement proposed here, encased within a dual-stage roughing filter system, holds promise for efficient simultaneous iron and hardness removal through passive filtration systems. These findings provide a practical, low-cost, and scalable solution to address the substandard groundwater quality in rural areas, while also serving as an important consideration for designing decentralized treatment systems in future counterpart regions facing similar dual-contamination issues.

2. METHOD

2.1. Study location

In many rural areas, communities rely on groundwater and surface water for their daily needs. Initially, the community in Dusun Ngandat, Mojorejo Village, Junrejo Subdistrict, Batu City, used water from Sumber Rejoso for their daily activities. However, the flow and discharge from Sumber Rejoso decreased during the dry season, so that clean water became scarce. In response, the local administration dug bore wells to control the water supply. Even with this solution, residents started complaining that the bore well water had a yellowish coloration and a funky metallic smell. These indicators imply high amounts of iron and hardness in the water, most likely beyond health limits. The presence of high quantities of iron and hardness can cause multiple issues, like clogging of pipes due to sedimentation build-up, yellow-stained laundry, and lower efficiency (soaps do not produce foam in high calcium concentrations). Extended exposure to such water could also lead to skin and eye irritation. Then, the treatment of bore well water is critical so that it is cleaned and used properly in everyday life. Extended exposure to such water could also lead to skin and eye irritation. Then, the treatment of bore well water is critical so that it is cleaned and used properly in everyday life.

The study was held in Dusun Ngandat, Mojorejo Village, Junrejo Subdistrict, Batu City. This research was conducted in Probolinggo Regency, East Java Province, Indonesia. Figure 1 shows the location and geographical coordinate points (7°54'15.97"S, 112°33'34.91"E) of the study area selected for this investigation. Mojorejo Village has an area of ±175 hectares (2.081 km^2) and is located in the east of Batu City at an altitude of about 650 meters above sea level. We chose this water source in this location because residents were already complaining about its poor quality, such as a yellowish coloration and a very strong metallic smell, which indicates an increased concentration of iron and hardness. As a result, they have been feeling extremely concerned about the groundwater being the source of water, and it cannot be used for daily use anymore. These contaminants are at levels above national health standards, hence represent risks to public health and the environment. Too much iron creates sediment that settles in pipes, creating clogs, inhibiting water pressure and possibly damaging plumbing systems. Meanwhile, high water hardness disrupts household tasks such as laundry and dishwashing, causing soap to be less effective and leave residue. In light of those challenges, Dusun Ngandat is an ideal location in which to determine the efficacy of combined vertical-flow and HRF at treating groundwater. The results from this study might also provide useful information for other rural populations with similar water quality challenges.

2.2. Equipment and materials

The present research discussed a combined vertical flow and horizontal flow roughing filter for reducing turbidity and hardness in bore well water. The different filtration media used were coconut fiber, activated carbon, zeolite, pumice stone, volcanic black sand, and silica sand. Laboratory-scale models were built to study the efficiency of the system for turbidity and hardness removal at a constant flow rate. For the

HRF, three different filter media arrangements were tested, whereas for the VRF, a fixed media configuration was deployed in each experiment. The aim was to determine which of these offered the best combination for effect on water quality. Figure 2 illustrates the laboratory-scale design of the combined vertical-flow, roughing filter, and horizontal-flow, roughing filter system, where Figure 2(a) shows the photograph and Figure 2(b) shows the schematic of the VRF and HRF model setup.

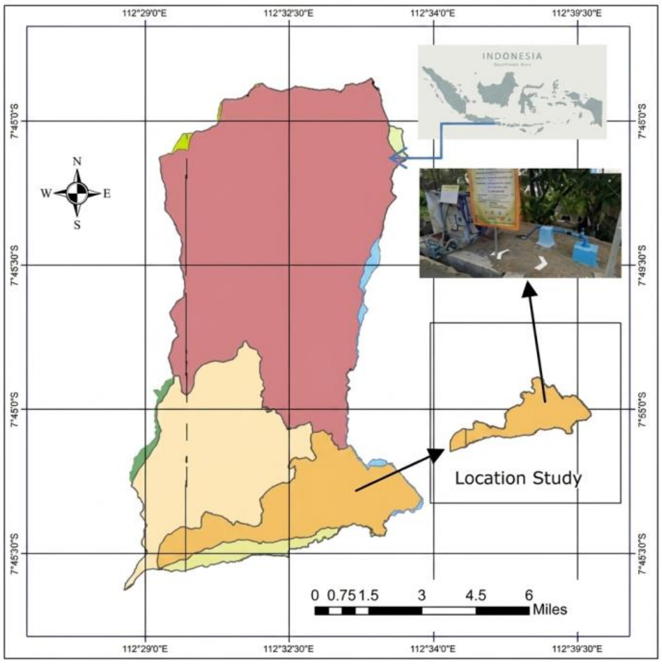
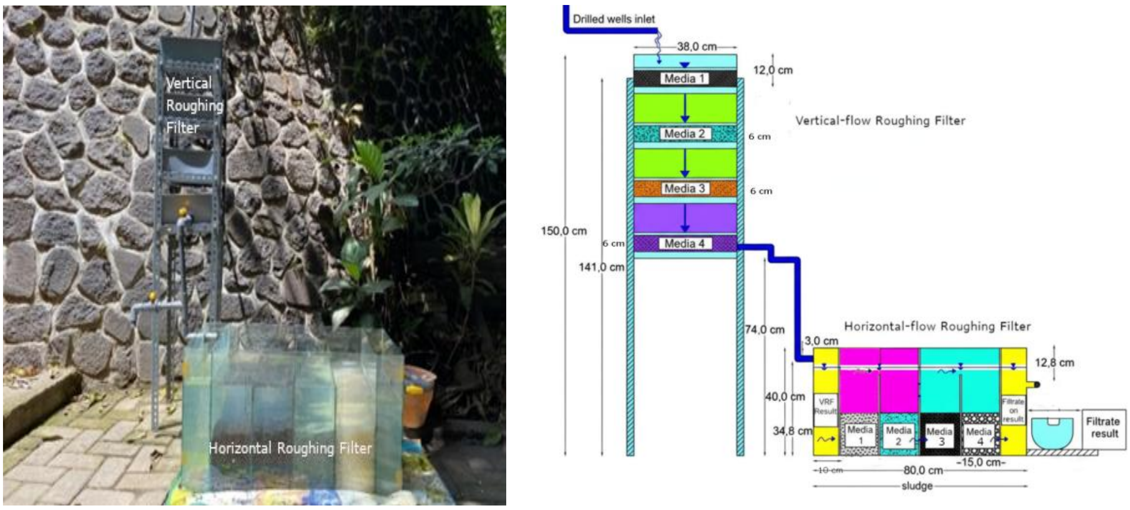


Figure 1. Location of the research



(a) (b)

Figure 2. Laboratory-scale design of the roughing filter for (a) photograph and (b) schematic of the VRF and HRF model setup

The main equipment used in this study is a system that combines a VRF and an HRF. The VRF works by letting water flow down through several layers of coarse filter material arranged vertically. In contrast, the HRF is set up so that the water to be treated flows horizontally [26]. These designs help heavier particles settle out and improve the biological processes that break down pollutants, including pathogens and organic matter. The multi-layered design of roughing filters allows for a gradual reduction in flow velocity.

This method helps to capture particles more effectively and supports the activity of microorganisms that break down pollutants.

2.3. Experimental filtration setup

The treatment system was a dual VRF and HRF combined unit designed as one, multi-level filtration gravity-driven system. It is composed of 4 plastic containers measuring 38×30×12 cm, which have been assembled on a bracket with a perforated height set at 150 cm called the VRF model. 0.5 mm holes were drilled into the bottoms of each container to allow the flow of water between layers. The HRF model was constructed on an aquarium glass tank (80×40×40 cm), with the thickness of the glass is 0.5 mm. The tank was partitioned into six sections, four for the filter media and two for collecting filtered water. To obtain a continuous flow between the VRF and HRF, 0.5-inch polyvinyl chloride (PVC) pipes were devised to ensure a continuous flow for the connection of the VRF and HRF. Besides the aforementioned, other tools employed throughout experiment included plastic buckets, sample bottles, water taps, rulers, and graduated cylinders to measure flow rate at each sensor location; drilling equipment; mobile phone cameras for documentation purposes; 0.5-inch pipes and pipe glue; shock threads and knee joints for assembly; stop valves to control flow through parts of the sensor system as needed glass glue (with cleaning cloths) for leaks. These tools aided the assembly, operation, and maintenance of the filtration system over the course of this study. Table 1 shows specifications of the filtration system. The whole system was run under gravity-driven flow conditions, as per the design specifications for roughing filters; a low velocity HLR was maintained. A total flow rate of 0.321 L/min was employed in this study, scaled from the actual bore well to match the scale model.

Table 1. Filter unit dimensions

Component	Dimensions (length × width × depth)	Function
Raw water tank	250-liter tank	Stores the bore well water prior to filtration.
VRF	4×(0.38×0.38×0.12 m)	Operates in upflow mode for initial coarse solids removal.
HRF	0.8×0.4×0.4 m	Operates in horizontal flow mode for fine particle sedimentation and interception.
Treated water collection tank	Plastic buckets	Stores the final treated effluent for sampling and analysis.

2.4. Filter media preparation and configurations

Descriptions of filtering media that were source, washed and cleaned in a standard laboratory for removing fine particles and dust are as follows; i) coconut fiber: used mainly for early separation by fine particle screening and filtration; ii) activated carbon: to adsorb organic matter, odor, and color; iii) silica sand ultrafiltration with 1 to 20 μm sized pores at high pressures is easy from physical removal of suspended solids as well as turbidity [27]; iv) zeolite: it is ion-exchange capacity also allows them for water purification because it targets hardness ions (Ca^{2+}, magnesium (Mg^{2+})) where they may come out into some metals; v) pumice stone: used as a lightweight, porous medium for high surface area, promoting both biological activity and physical straining; and vi) volcanic black sand: an available alternative filtration medium. The raw water in this study was taken from an existing bore well located in Dusun Ngandat, Mojorejo Village, Junrejo Subdistrict, Batu City. The thickness of each filter medium in the VRF was 6 cm, while for the HRF it was 15 cm. For the VRF, the same arrangement of filter media included in all models was used; the order of layers from top to bottom was: coconut fiber–activated carbon–zeolite–pumice stone. On the other hand, based on experimental variations, there were three different media arrangements in the HRF: model 1: silica sand–activated carbon–zeolite–pumice stone; model 2: volcanic black sand–activated carbon–zeolite-pumice stone; and model 3: volcanic sand–activated carbon-zeolite-silica sand. These variations were experimental and were made to assess how different media compositions in the horizontal filter would affect the quality of water, especially iron concentration and hardness.

The dual filtration roughing filter (DFRF) system was first designed as a gravity-fed passive treatment unit composed of two stages: a VRF downstream of an HRF. The VRF represented the initial removal mechanism for suspended solids and particulate-associated contaminants, whilst contact time was increased in the HRF to encourage quiescent sedimentation, sorption, and primary stabilization. VRF (effective filtration surface area: 0.38×0.38 m) and HRF (cross-section of the surface area in width of 0.15 m; length of 0.40 m). The whole system was conducted under a continuous flow rate of 0.321 L/min ($3.21.10^{-4}$ m^3/min) during the experiment period. The two filtration stages were packed with graded gravel media, which were placed into the two tanks comprising four stratified layers. The VRF consisted of a total media depth of 24 cm (4 layers×6 cm), whereas the HRF had a media depth of 60 cm (4 layers×15 cm). Before placement, the media were washed thoroughly to remove fines and ensure consistent porosity.

2.5. Experimental procedure

The pre-treatment system in this study used a two-step process, including VRF and HRF. The vertical filter had four sections, and the horizontal filter had six. Water was supplied from a 250-liter tank, which was connected to the filter system using PVC pipes. The vertical and horizontal filters were connected manually with 0.5-inch PVC pipes. The entire system was supported by a frame made of perforated iron angle bars. The filtration system was designed to measure two important water quality indicators: iron and hardness. The source of the water analyzed was taken from a drilled borehole in Dusun Ngandat, not far from where the experimental model was placed. The diagram of a VRF and HRF system is shown in Figure 2.

In order to compare and contrast data, water samples were collected 240 minutes (4 hours) after continuous filtration. The samples were subsequently taken for laboratory analysis, and conventional approaches were used to accurately detect the iron and hardness levels. Assessment of this filtration system in terms of the water quality standards regulation [25] was possible through comparison with regulation benchmarks for safe, potable water.

The filter media were thoroughly washed and dried, and then placed into the filter compartments according to the descriptions of the experiments. Water from an existing bore well was stored in a 250-liter tank by pumping it into the combined VRF and HRF system via a gravitation feed of ½ inch PVC pipe. The flow into the filtration system was regulated by a stop valve and measured with a graduated cylinder and stopwatch. The flow rate used in this study (0.321 L/min) was scaled from the actual bore well flow. After 4 hours of filtration of treated water, samples were collected at the outlet end using clean sample bottles and analyzed in the laboratory following the procedures given in Table 2. This protocol was repeated for all of the models, and the filter media were exchanged according to the order described before for each version. The final results were compared to the criteria from regulation [25].

Table 2. Methods and standards for laboratory analyses of treated water samples

Parameter	Analytical method	Standard limit [25]
Iron content	Volumetric/titration method (e.g., permanganate or dichromate method)	1.0 mg/L
Total hardness	Atomic absorption spectrophotometry (AAS) for calcium (Ca) and magnesium (Mg)	500 mg/L (as $CaCO_3$)

Hardness, defined by Ca^{2+} and Mg^{2+} ions, was determined by measuring the concentration of these individual ions using the AAS technique. The total hardness was then calculated and expressed as an equivalent concentration of $CaCO_3$.

The HLR calculated for each of the roughing units were used to operate the system as follows: a VRF HLR: 3.70×10^{-5} m/s (0.13 $m^3/m^2\cdot h$); HRF HLR: 8.92×10^{-5} m/s (0.32 $m^3/m^2\cdot h$), which corresponded with their surface area, and which flow rate was applied in L/min at 0.321. The corresponding hydraulic retention time (HRT) for the VRF and HRF was about 5.0 h and 5.3 h, respectively, leading to a combined theoretical HRT of 10.3 h for full DFRF as in system design. No indication of clogging was detected during the entire operating period, and headloss is stable. Due to the emphasis on short-duration performance testing with this study, backwashing cycles were not performed, and long-term requirements could not be assessed.

2.6. Data analysis

The removal efficiency for iron and total hardness for each filter configuration was determined with (1) and (2).

$$Hardness\,reduction\ (\%) = \frac{C_{influent}-C_{effluent}}{C_{influent}} \times 100 \tag{1}$$

$$Iron\,reduction\ (\%) = \frac{C_{influent}-C_{effluent}}{C_{influent}} \times 100 \tag{2}$$

Where $C_{influent}$ is the concentration of the contaminant in influent (raw bore well water), and $C_{effluent}$ is the concentration of the contaminant present in effluent (final treated water).

Water samples used in this study included both the raw bore well water and filtered effluent from the DFRF system. The well water was collected into a 250 L tank, and then pumped to this vertical-flow filter at a flow rate of 0.3 L/s through four layers of filtration media from top to bottom. The partially treated water was then directed into a horizontal-flow filter, which comprised six chambers: two for collecting water during the weakest point of the treatment process and four containing different filtering materials. In-situ sampling as well as laboratory analysis were performed for two concentrations: iron and hardness from the water quality parameters. The removal efficiencies for both parameters were calculated as the difference between influent and effluent concentrations provided after 4 hours of operation. The limited data collected from only one effluent allowed us to develop neither time-dependent assessment, such as breakthrough curves, media saturation profiles, nor performance trend graphs. Thus, the results outlined here should be considered as initial performance indicators for the DFRF system. A comparison of all measured values, and environmental health quality standards and water health requirements by the Ministry of Health Republic Indonesia [25]. Table 3 shows the characteristics of influent obtained from groundwater well before filtration.

Table 3. The influent parameter of iron and hardness

Variable	Model 1	Model 2	Model 3
Iron in mg/L	6,059	5,882	5,971
Hardness in mg/L	532	425	514
Turbidity in nephelometric turbidity unit	101	101	101
pH	7.1	7.1	7.1

3. RESULTS AND DISCUSSION

As discussed in previous sections, the combined VRF and HRF system was tested using three different versions of the reff in-water configuration, denoted as model 1, model 2, and model 3. The arrangement of the filter media is what distinguishes these models. All three models used a static HRF media composition, and the HRF model was characterized by a specific media combination. Comparison of influent water and model 1, model 2, and model 3 for different water quality parameters is presented in Table 3. Table 4 summarizes the variation of iron concentration in the bore well water (with and without filtration), as well as the related quality standards provided [25].

Table 4. Iron test results

Model	Iron (mg/l)	Standard (mg/l)	Remarks
Influent water from bore well (before filtration)			
Model 1	6,059	≤1	Exceeds
Model 2	5,882	≤1	Exceeds
Model 3	5,971	≤1	Exceeds
Effluent (after filtration)			
Model 1	0,588	≤1	Meets
Model 2	0,706	≤1	Meets
Model 3	0,147	≤1	Meets

As shown in Table 4, model 3 exhibited significantly higher removal of iron from bore water than the other models. The model uses a raw flow roughing filter with layered volcanic sand, activated carbon, zeolite, and silica sand. It has been previously reported that gravel at different sizes was able to aggregate suspended solids and successfully improved the rates of sedimentation and absorption [26], while charcoal, in combination with coagulant, further reduced the turbidity level due to its small diameter, large surface area, and high porosity areas that assist in both settling and adsorption [28]. Activated carbon also adsorbs dissolved contaminants, and its extensive surface area enables the physical filtration of particulate pollutants [29]. This makes activated carbon very good for water purification due to its ability to remove both heavy metals and organic compounds, thus enhancing the quality of treated water [30], [31], while zeolites have displayed considerable capabilities in extracting heavy metals from water supplies by utilizing ion exchange mechanisms enabling them to selectively seize and hold cations from a water source reducing the amounts of pollutants such as iron or manganese in most cases of water treatment performed [32], [33]. The grain size of silica sand is also closely related to its filtration efficiency. For example, Valentukevičienė [34] showed that finer silica sand promotes higher administration rates of contaminants like iron and ammonium ions (95% removal efficiency at certain conditions). Silica sand is suitable for treating effluents containing complex contaminants such as manganese and iron due to its chemical stability and non-reactive property. The catalytic behavior of such complexes had been previously investigated, and several modifications to gain enhanced catalytic performance from them were also suggested [35], [36]. Fairuz *et al.* [37] highlight the importance of adding volcanic sand to vertical flow roughing filters that also contain such materials as zeolite and activated carbon. Enhanced contact time can be achieved through variable thickness of volcanic sand layers, which could improve the quality of rainwater and use volcanic sand to reduce iron, manganese, and turbidity from bore water.

The filtered output has a diminished iron rust flavor due to the lowering of iron content in the water. This results from the impact of filtration media, such as zeolite and activated carbon. The zeolite employed may adsorb diverse chemicals, ions, and organic molecules from water, together with an electric charge that attracts and binds these things, including heavy metals, ammonia, phosphates, and organic contaminants. Activated carbon can adsorb odors, iron concentration, and color in well water, leading to alterations in the water's color, odor, and taste post-filtration. Natural zeolites possess significant adsorption and ion-exchange capabilities, allowing them to soften water by removing metal ions, organic impurities, and microorganisms [38], [39]. For instance, zeolites can effectively filter harmful microbes and nitrogen compounds from drinking water due to their porous structure, which acts as a molecular sieve [40].

Table 4 demonstrates that the combined VRF and HRF models effectively reduced the iron concentration in the bore well water. According to regulation [25], the maximum allowable iron concentration is 1 mg/L. The highest iron concentration in the samples taken from the bore well before treatment was 6.059 mg/L in model 1, which exceeds the standard threshold. The iron concentration after filtering was reduced to 0.588 mg/L, 0.706 mg/L, and 0.147 mg/L for models 1, 2, and 3, respectively. From the data analysis, it is evident that all three models applied in this study successfully reduced the iron levels in the water. The high removal of metals, including iron, was due to the conventional filtration media comprising activated carbon, zeolite, and volcanic sand that strongly adsorbs many metal ions [41].

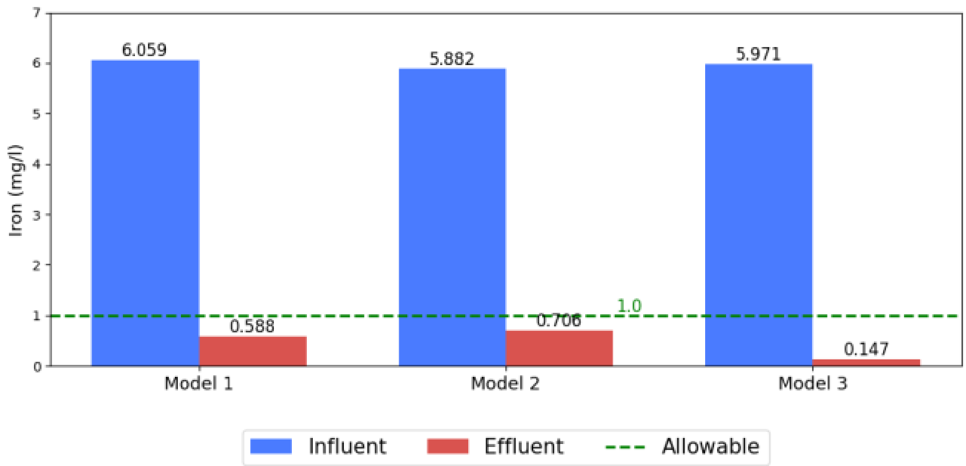
Figure 3 shows the visual differences in the bore well water from before filtration process, as in Figure 3(a), and after filtration process, as in Figure 3(b). The water before filtration was turbid, yellowish, and had visible sediment settled at the bottom. This discoloration is often the result when dissolved ferrous iron (Fe^{2+}) in groundwater comes into contact with oxygen, causing it to oxidize and generate ferric iron (Fe^{3+}). Ferric iron therefore precipitates out in the form of solid particles, which causes a yellow color and increased turbidity (increased total suspended solids (TSS)) [42]. Four hours later, the water was clear and free of sediment. This increase in clarity and color is through the filtration media used. Volcanic sand proved to be one of the main filter materials, effectively removing dissolved organics responsible for the color and turbidity. The roughing filter also helps in the process through a thick layer of activated carbon that removes remaining turbidity and color compounds from water by means of adsorption. It is worth noting that by using more and more fine filter media in the roughing filter, filtration efficiency increased thanks to some aids against small particles [43].

(a) (b)

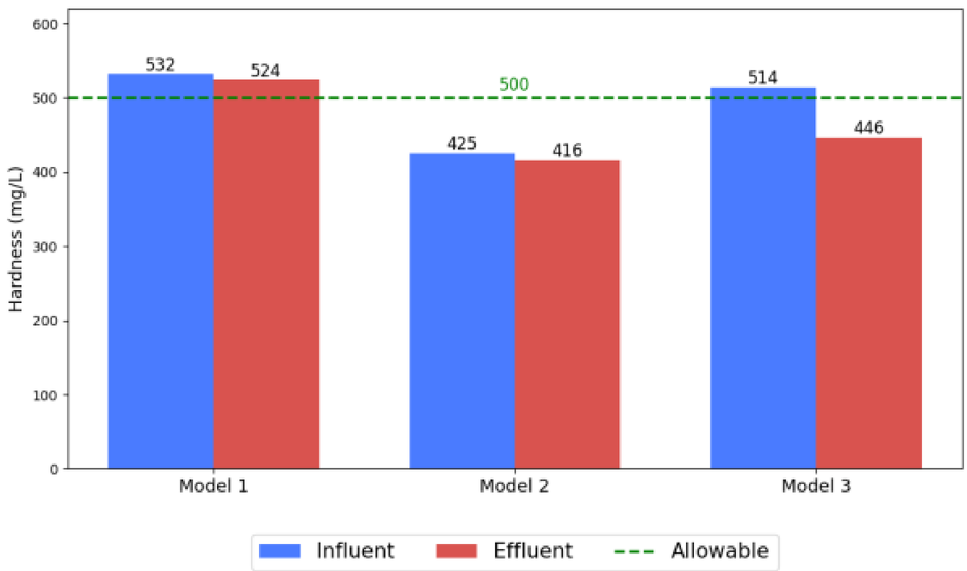
Figure 3. Comparison of bore well water samples of (a) before and (b) after filtration

Figure 4 shows the decrease in the concentration of iron and hardness. Figure 4(a) depicts the reduction of iron concentration in the three treatment models over time, which confirms that filtration systems are effective. Of all models, model 3 demonstrated the highest removal efficiency with a reduction in iron concentration from 5.971 mg/L to 0.147 mg/L as compared to 5.882 mg/L (model 2) and 6.059 mg/L (model 1), and the removal achieved is significant owing to the adsorptive properties of activated carbon due to its ability to convert dissolved iron into an insoluble form that can be removed during filtration process. The use of volcanic sand, which is also used in the filtration media, not only increases the removal efficiency of metals due to its inherent capacity for absorption (particularly iron). Moreover, zeolite contributes a pore structure and ion-exchange for improving the system's properties. Zeolite, with its negatively charged aluminosilicate frameworks, allows for the binding of positively charged ions such as Fe^{2+}, Al^{3+}, Ca^{2+}, and Mg^{2+}, which are generally found in groundwater. Its pore structure also facilitates molecular sieving, allowing pollutants with a size large enough to be filtered and absorbed accordingly.

Figure 4(b) shows the decrease in water hardness for the three filtration models, which was not considerable. The hardness of water is mainly due to the presence of Ca^{2+}, Mg^{2+}, and Fe^{2+} salts, but more specifically, it is due to calcium and magnesium ions. These minerals usually leak into groundwater via geological weathering, where acidic rainwater dissolves limestone and dolomite, both of which are high in Ca^{2+} and Mg^{2+}. The aforementioned metal ions not only contribute to the hardness of water but also possess health-threatening properties if not well treated [44]. Consequently, high hardness content deducted from bore well water was involved very significantly in the study site. Model 1 had the highest initial hardness of 532 mg/L, which was greater than the recommended standard value of 500 mg/L; only a slight decrease was observed after four hours of filtration (524 mg/L). In model 2, the hardness was lowered more effectively from an initial value of 490 mg/L to a final value that brought it within acceptable limits (416 mg/L). The greatest reduction was seen in model 3, which reduced hardness from 514 to 446 mg/L. The measured reductions of hardness are primarily contributed to by activated carbon in the filtration system. Activated carbon is an effective adsorbent which can remove metal ions and various other impurities from the water. However, this cannot provide insight into the long-term efficiency and breakthrough behavior because only one data point was collected. The kinetic iron removal generally decreases as the media become saturated or coated with static precipitates, and extended monitoring must be conducted to determine the most appropriate interval for cleaning or replacement of media.



(a)



(b)

Figure 4. Decrease in the concentration of (a) iron and (b) hardness

Data in Table 5 demonstrate water hardness test results for the three types of filtration models versus initial (unfiltered) bore well water. The average arrangements to decrease mineral hardness for the three models were not reduced, and model 1 showed the worst performance. For model 1, hardness was initially found as high as 532 mg/L, and structural filtration did not yield a significant change, and it was still above the acceptable standard of 500 mg/L for treated water. A slight success was observed in model 2, where a decrease from 425 mg/L to around 415 mg/L was found while using a structural filtration mechanism, but this too is a minuscule reduction, and the last value met the criteria for treated water quality. Regarding hardness, the biggest influence was seen from model 3, where it decreased from 514 to 446 mg/L, estimating a lowering of 68 mg/L. Although this was an improvement, the level of treated water remained within the border properties for all models, which could require further treatment to reach optimal levels of hardness.

Table 5. Hardness test results

Model	Result (mg/l)	Standard (mg/l)	Remarks
Influent water from bore well (before filtration)			
Model 1	532	≤500	Exceeds
Model 2	425	≤500	Meets
Model 3	514	≤500	Exceeds
Effluent (after filtration)			
Model 1	524	≤500	Exceeds
Model 2	416	≤500	Meets
Model 3	446	≤500	Meets

The percentage reduction in iron and hardness retention after filtration is presented in Table 6. Model 3 had the highest percentage of reduction from all three models. It used volcanic sand–activated carbon–zeolite–silica sand in the HRF and coconut fiber–activated carbon–zeolite-pumice stone in the VRF, resulting in a decrease of iron concentration by 97.5%. By contrast, the decrease in hardness for all models was relatively small, meaning that the corresponding filter media used were not very effective at targeting hardness. However, model 3 yet displayed the maximum hardness reduction, at 13.2%. Zeolite is a good cation exchange agent that reduces hardness. When bore well water containing Ca^{2+} and Mg^{2+} ions of high hardness pass through the filter, these ions are exchanged with sodium (Na-) ions within the zeolite framework. But of course, as zeolite gets saturated by sodium ions, this saturation limits its ability to exchange ions.

Table 6. Reduction efficiency of iron and hardness

Experiment	Iron (%)	Hardness (%)
Model 1	90.3	1.5
Model 2	88.0	2.1
Model 3	97.5	13.2

A few limitations should be considered with the interpretation of these study results. One major limitation is that only one effluent data point was taken after 4 hours of operation, precluding the visualization of temporal removal trends, breakthrough progressions, and behavior concerning media saturation. Therefore, the results reflect just the early-stage performance of the DFRF system. Another limitation in the study was the relatively short operational duration, which limited insights into long-term hydraulic behavior, such as clogging development or backwashing requirements (there were no signs of clogging during this test, and no backwash cycles had occurred). The raw water quality in this study was also taken at one time, so seasonal fluctuations were not recorded; especially turbidity changes and other parameters such as iron and hardness differed from dry to rainy seasons. Such variability may affect the robustness of the system in realistic operating conditions. It was also not possible to assess for long-term media fouling, biological growth, or headloss accumulation that occurred over time, all of which are essential for determining maintenance schedules and predicting the lifetime of a filter. Recent evidence to support the DFRF as a cost-effective treatment technology is convincing, but expanding its applicability could be challenging in rural or resource-constrained settings with different water demands and building materials, land, and technical expertise. The above approaches provide details on the time frame of these aforementioned phenomena, but future studies should combine long sampling duration and multi-season raw drinking water monitoring with continuous hydraulic characterization and routine backwashing tests in order to generate comprehensive breakthrough curves and media saturation profiles that have implications for longer-term operation.

Also, it is essential to assess material availability and the construction possibility of appropriate filtration systems to promote local sourcing (which lowers transportation costs) and enable community involvement in the assembly and maintenance process. Especially when using native labor and regionally available materials, construction costs are still fairly low. A filter must also be maintained regularly in order to perform properly, which includes cleaning the inlet screens, removing sediment build-up within the filter media, and resurfacing or agitating the filter media to avoid clogging, among other things. The assembly, operation, and maintenance of the systems can be considerably improved over the long term if communities are actively involved; local operator groups with training to develop easy-to-follow maintenance schedules or checklists will help ensure ownership and that rectification measures are taken in time. Involving the public in this way leads not only to less disruption of operations but also helps build capacity at the level of local communities, allowing for self-sustaining management of decentralized systems.

A practical equilibrium is reached by combining vertical-flow and HRF systems that bring about significant reductions in iron and hardness. It is not expensive to operate, and it can be built using materials found nearby. This system is a good fit for water supply projects that are decentralized, particularly when there is a need for something easy to use, affordable, and that gets the community involved. Crucially, the system minimizes reliance on chemical additives and energy-intensive processes; as a result, it enhances community access to safe water in resource-constrained settings, which aligns directly with SDG 6 (clean water and sanitation) targets. The dual-flow system can also serve as a complementary process to biochar-amended media or membrane-based post-treatment, functioning as an efficient pre-treatment unit, prolonging the life and performance of downstream processes. Overall, the integrated vertical-flow and HRF system will help to lead to further decentralized, sustainable water treatment solutions that enable community development for equitable human access over space and through time.

4. CONCLUSION

Studies on VRF and HRF combinations will help to identify the efficient operational parameters which could be used for improving the quality of bore well water with reference to iron concentration. The system performance varied widely based on the arrangement of the filter media, unlike all models, which demonstrated high iron removal efficiency and low hardness reduction. Out of all the tested configurations, model 3 performed the best and could remove nearly all of its iron content (nearly 98%), having had its media combination optimized in value terms during previous runs. The most effective solution was realized by combining the use of media capable of adsorption and ion exchange, removing dissolved metals and improving total water quality markedly. The results show that appropriately designed roughing filter systems are an inexpensive and sensible alternative for decentralized water treatment. In addition, digital water has emerged as one of the most promising trends in building sustainable water infrastructure, with many internet of things (IoT)-enabled systems coming to sustainable and practical water solutions. Real-time monitoring of critical water quality parameters through smart sensors and connected devices is becoming a reality, which helps us quickly identify system failures through rapid detection so that prompt action can be taken where needed, optimize maintenance (right asset at right time), and ultimately increase user confidence. These digital technologies enhance operational efficiency, allowing for data-driven control over treatment performance for a more intelligent approach to water management. At the same time, to reduce energy consumption and ensure reliable operation in off-grid or low-resource environments, there has been a growing uptake of solar-powered pumping systems, which is a very big contributor to the overall sustainability of off-grid (and desert) water supply solutions. Future studies should investigate the combined use of IoT-assisted monitoring and solar-powered operation within passive filtration systems, including the development of low-cost sensor networks, automated maintenance alerts, energy-optimized pumping controls, and predictive analytics frameworks to improve long-term system performance and community scalability. Future research should also focus on enhancing hardness removal, extending filter lifespan, and integrating smart monitoring, predictive analytics, and energy-efficient controls to support long-term and scalable water treatment solutions.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualisation
M : **M**ethodology
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D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualisation
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

INFORMED CONSENT

Not applicable. This study did not involve human participants, human data, or any personally identifiable information. All data used were either publicly available, fully anonymized, or derived from non-human sources, and therefore no informed consent was required from individuals.

ETHICAL APPROVAL

Not applicable. This research did not involve human subjects, human biological materials, or experimental procedures on animals. The work was conducted solely on computational models, publicly available datasets, or non-sensitive data that did not require intervention with living organisms. Therefore, ethical approval from an institutional review board or animal ethics committee was not necessary for this study.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [AWWS], upon reasonable request.

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