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Comparative Analysis of the Efficiency of Reverse Osmosis and Hydroxyapatite for Fluoride Removal in Water: A Case of AUWSA

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ABSTRACT

Water treatment technology selection depends on contaminant type and budget. Fluoride removal from water is particularly challenging, requiring non-conventional treatment technologies (Radwan, 2023). Several regions in Tanzania, including Arusha City, are affected by fluoride contamination. With a population of 617,631 (Census, 2022), only 117,763 people currently have access to clean water supplied by AUWSA. This study aimed to compare the efficiency of Reverse Osmosis (RO) and Hydroxyapatite (HAP) in fluoride removal as a strategy to address water quality and supply challenges. Experiments were conducted using 6 m³ of raw water with fluoride concentrations ranging from 5.1 mg/L to 6.83 mg/L, sourced from boreholes. The HAP pilot plant was tested at 30-minute intervals from 8:00 AM daily for 21 days, while the RO system was tested with the same water volume at 5-minute intervals over the same period. Laboratory analyses of raw and treated water revealed that HAP had a lower fluoride removal efficiency of 91.51% to 93.41%, compared to RO, which achieved 96.05% to 97.66% removal efficiency. It was also revealed that RO loses about 30% of water during treatment, while HAp doesn't lose any. Moreover, HAp uses locally available biogenic materials for treatment, enhancing sustainability. The findings suggest that the HAP treatment system is a practical and sustainable solution, offering effective fluoride removal while remaining affordable and energy-efficient, making it a viable choice for communities in need of clean and safe drinking water. This research addressed the problem of excess fluoride concentration in water and availability and access of clean water. Further research is recommended to evaluate the environmental implications of waste disposal following HAP media regeneration and the management of reject water from the RO filtration process. This assessment should focus on potential ecological risks, long-term sustainability, and the development of environmentally friendly disposal or reuse strategies.

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INTRODUCTION

Water supply and Sanitation refer to the system of distributing water of good quality, sufficient quantity and feasible within the community while removing wastewater. 60 – 80% of water used is generated as wastewater (WATER, 2009). The provision of water to the community is essential for domestic purposes and other daily activities, such as economic and social activities. From an economic perspective, water is essential for agriculture and livestock development. Furthermore, providing a clean and safe water supply will reduce the number of waterborne diseases; this saves time for other productive activities, such as agricultural and commercial activities. Since water exists underground, surface and above surface, it is exposed to contamination and hence the need for treatment before consumption is inevitable so as to get access to clean and safe water (Richter, 2014). Slightly more than half the population of Tanzania is estimated to have access to clean and safe water. Rural areas are estimated to have improved from 70.1 per cent in 2020 to 74.5 per cent in 2022, while urban regions improved from 84 per cent to 86.5 per cent (UNICEF, 2022).

Fluoride contamination remains a significant public health challenge in developing countries, particularly in regions where groundwater is the primary source of drinking water (Fadaei & Niu, 2021). In Tanzania, certain areas experience severe fluoride contamination, leading to adverse health effects such as skeletal and dental fluorosis.

In Arusha City, the issue of water quantity and quality is critical, as many water sources exceed the World Health Organization's (WHO) fluoride limit of 1.5 mg/L (WHO, 2011). With a daily water demand of 108,000 cubic meters and a production capacity of only 96,000 cubic meters, the city struggles to provide fluoride-safe water due to the limited availability of low-fluoride sources.

Fluoride is essential in trace amounts for bone mineralization and protection against dental caries; however, excessive fluoride intake leads to dental fluorosis (enamel decay), osteoporosis, brittle bones, arthritis, brain damage, infertility, cancer, Alzheimer's disease, thyroid disorders, and other serious health conditions (Mbabaye, 2018). Fluoride enters water sources through natural geological processes, industrial emissions, and agricultural runoff, making it a complex environmental and health concern.

Arusha City is among the regions in Tanzania where water sources are highly contaminated with fluoride, posing serious health risks to the population (Mero et al., 2020). Excess fluoride in drinking water has been linked to dental and skeletal fluorosis, brittle bones, and other systemic health complications (WHO,2011). In Arusha, fluorosis and brittle bones are among the most prevalent fluoride-related health issues. Recognizing the urgency of this issue, the Government of the United Republic of Tanzania, through the Ministry of Water, initiated a fluoride mitigation project to address both water quality and supply challenges.

The project was approved in September 2015 and officially commenced in December 2015. Its primary objectives were to reduce fluoride contamination, improve public health, and increase water availability. As part of this initiative, the government established a Reverse Osmosis (RO) (Ahuchaogu, 2018) plant and a pilot-scale Hydroxyapatite (HAP) system at the Arusha Urban Water Supply and Sanitation Authority (AUWSA) sites (Tanzania Ministry of Water, 2016).

Recent advancements in fluoride removal technologies have focused on the development of functional nanomaterials and modifications of hydroxyapatite (HAP). Innovative synthesis methods have led to the creation of nano-hydroxyapatite adsorbents, which exhibit enhanced efficiency in removing contaminants from

aqueous solutions (Telli *et al*, 2025). Additionally, the integration of aluminum hydroxide with zeolites has resulted in composites with improved fluoride adsorption capacities, offering promising alternatives for water treatment applications (Dessalegne, Zewge and Diaz, 2017).

Fadaei (2021) conducted a study on the comparison of different floride removal techniques. In his study, he compared several techniques such as adsorption (bio-adsorbents, NPs, and bioremediations), ion exchange, NF, freeze concentration, RS, electrolysis, coagulation, MOFs, and EC. The study concluded that our future needs include, cheap, highly developed systems, with low waste, and maximum utilization of the accessible waste at the full scale to continue the removal of fluoride.

Due to the increasing effect of fluoride-related health issues and lack of cost-effective treatment methods, this study evaluates the comparative efficiency of RO and HAP in fluoride removal and recommends the most environmentally sustainable and cost-effective technology for large-scale application.

METHODS AND MATERIALS

Materials

Water samples were collected from AUWSA boreholes in Arusha City, Tanzania, where fluoride levels between 5.10 mg/l to 6.83 mg/l. These samples were used in the study to compare the effectiveness of reverse osmosis and hydroxyapatite in fluoride removal from water.

The study used a stock of HAP particles obtained from HRBAUER HAP, a manufacturer based in Kenya. The commercially available particles exist in 50 Kg per bag, and only 750 Kg were poured into a stainless steel container that was used for fluoride removal experiments. On the other borehole site with the RO plant, similar water fluoride content samples from boreholes were tested for real-world RO operations, and the samples were taken in the laboratory for analysis. The selection of these two methods is due to their availability in the area and has been considered by the water authority as feasible techniques for water treatment.

Methods

Treatment Systems

Reverse Osmosis: In reverse osmosis, external pressure is applied to the concentrated (contaminated) side of a semipermeable membrane, counteracting the natural osmotic flow. This applied force compels water molecules to migrate against their usual gradient, effectively separating them from dissolved impurities. As a result, only pure water passes through to the dilute (treated) side, while contaminants are left behind.

A reverse osmosis (RO) system was installed at one of the selected borehole sites for experimental analysis (Ahuchaogu, 2018; Garud, 2011). The system was configured to pump water samples through Pentair tubular membranes, each measuring 1 meter in length and 0.2 meters in diameter. These membranes contained hollow fiber elements with a pore size of 0.5 micrometers. A total of four membranes were arranged in parallel within dedicated housings, through which raw fluoride-rich water was pumped. The feed pressure pumps used had a combined capacity of 35 kWh, with each pump operating at 17.5 kWh. The inlet and outlet flow rates were set at 84 m^3 per hour for the two parallel RO lines. The experiment was conducted under controlled conditions with a constant volume approach, allowing variations in time (days) and mean daily fluoride concentration measurements. The number of cycles or batches processed was recorded at five-minute intervals during each RO operation. Consequently, twelve cycles were completed per hour over a 21-day experimental period. Water samples were collected from both the feed and permeate sumps for comprehensive water

quality analysis, ensuring a detailed assessment of fluoride removal efficiency.

Hydroxyapatite: Fluoride remediation using hydroxyapatite (HAP) operates through a combination of physicochemical mechanisms, redominantly adsorption, ion exchange, and precipitation. These processes exploit the structural and chemical properties of HAP, facilitating the selective uptake and immobilization of fluoride ions (F^-) from aqueous systems. At the second experimental site, a pilot-scale Hydroxyapatite (HAP) plant was utilized for fluoride removal (Ghedjemis, 2022, Nayak, 2021). The HAP media, which consisted of 10-nanometer particles, was placed in a specially designed treatment vessel. The vessel was positioned at a 90-degree angle to maximize the contact between the water and the HAP, which improved the efficiency of fluoride adsorption. Each filter contained 375 kg of HAP media with a fluoride adsorption capacity of 2.625 kg per filter. Raw water rich in fluoride was passed through the HAP media, maintaining a contact residence time of 30 minutes at a flow rate of 6 cubic meters per hour. The experiment was conducted under controlled conditions with a constant volume approach, while varying exposure times across different days to determine mean daily fluoride removal efficiency. Given that each experimental session lasted for five hours, fluoride removal efficiency was evaluated in discrete treatment cycles, recorded every 30 minutes. Consequently, ten cycles were completed per day over the 21-day experimental period. Water samples were systematically collected from both the inlet and outlet pipelines for laboratory analysis.

Chemical Analysis

The chemical composition analysis of water samples was conducted to determine the presence and concentration of various elements and compounds. This analysis was essential for understanding the physicochemical characteristics of the treated water. Water samples were systematically collected from both the Reverse Osmosis (RO) and Hydroxyapatite (HAP) treatment systems and subjected to laboratory testing at the Arusha Urban Water Supply and Sanitation Authority (AUWSA) facility.

A comprehensive suite of analytical methods was employed, including fluoride concentration measurement using a fluoride ion-selective electrode meter, pH determination via a calibrated pH meter, and assessments of Total Dissolved Solids (TDS), Electrical Conductivity (EC), and turbidity using standardized laboratory protocols. The obtained results were systematically recorded, analyzed, and subsequently presented in the Results and Discussion section.

Statistical Analysis

This was conducted to give the quantitative results of the study. The gathered data from Reverse Osmosis and Hydroxyl apatite before and after treatment were further analysed, recorded and computed in terms of average and standard deviations. The mean and standard deviations of inlet raw water and outlet treated water for both RO and HAP were calculated and compared in terms of their removal efficiencies.

Treatment energy computation

Reverse Osmosis

For the RO experiment, two parallel units were used, resulting in an average hourly energy consumption of approximately 55 kWh. This was determined by monitoring the electrical meter and summing the energy usage of three pumps: an 8.5 kWh feed pump, a 17.5 kWh pressure pump, and a 1.5 kWh dosing pump. Each RO unit consumed 27.5 kWh, leading to a total of 55 kWh for both units.

Hydroxyapatite: The HAP experiment consumed approximately 15 kWh, utilizing a single pump to transfer water from boreholes to a raw water storage tank before being directed into a vertical vessel containing HAP media for filtration. The

total daily operational cost was approximately 145,000 TZS, covering gas tank procurement, electricity, and sodium hydroxide for media regeneration. The regeneration of hydroxyapatite (HAP) after fluoride adsorption is crucial for maintaining its efficiency in long-term applications. Sodium hydroxide (NaOH) with a concentration of 0.1-0.5 M solutions at moderate temperature (25-50 ^{o}C is commonly employed as a regenerant due to its ability to desorb fluoride ions (ion exchange) and restore the active sites of HAP. The waste is normally neutralized by a weak acid to a pH of 6-8 before disposing to the environment.

RESULTS AND DISCUSSION

Water parameters from the selected boreholes before treatment

Water samples taken from seed farm boreholes at the Ngaramtoni AUWSA site were measured to test their fluoride concentration level. Other water parameters like turbidity, pH, Total dissolved solids and Electrical Conductivity were also measured to assess the water quality to determine if it complies with the prescribed standards before any treatment (TBS, 2018). The mean and standard deviations of the fluoride, Total Dissolved Solids, Electrical Conductivity and turbidity before any treatment were measured. The summary of the results indicating the mean values of fluoride, TDS, EC, pH and turbidity are presented in Figure 1. Water parameter after RO and HAP treatment

The characterized raw water samples subjected to two treatments indicated that RO demonstrates superior efficiency in reducing TDS levels, making it the preferred method for desalination and purification where dissolved salts need to be removed. On the other hand, HAP may be more suitable for specific contaminant removal rather than general TDS reduction. Figure 2 shows the outlet water TDS from RO and HAP, respectively.

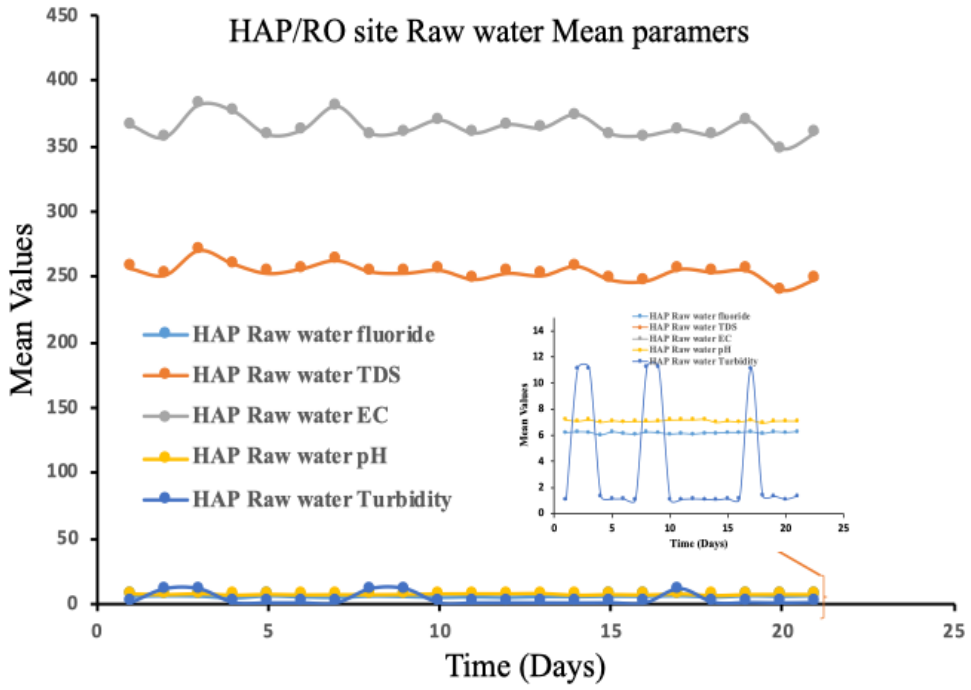

Figure 1: Raw water Mean parameters with an insert showing the bottom three patterns.

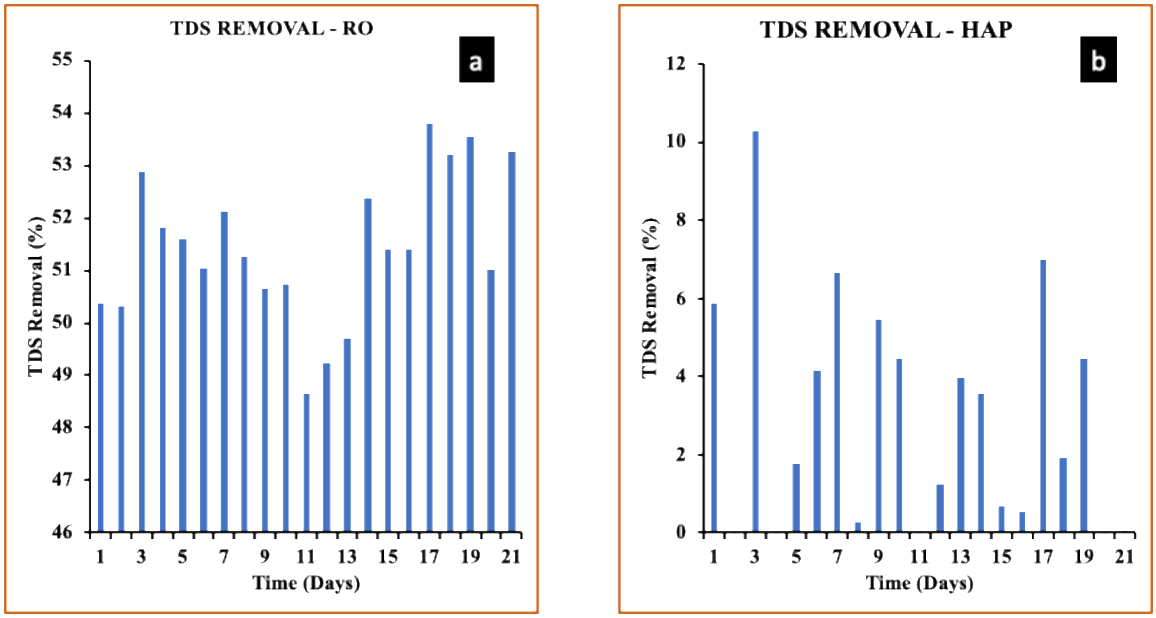

Figure 2: TDS removal from a) RO and from b) HAP.

Figure 3 shows the reduction of water electrical conductivities from RO and HAP treatment methods. The results suggest that RO shows consistent reduction in electrical conductivity across different samples in the period of 21 days, indicating that RO effectively removes dissolved salts and ions. The relative uniform bar heights suggest the high efficiency of RO. On the other hand, HAP, which is known for ion exchange properties for specific elements shows greater variability in conductivity removal. The results suggest that HAP's removal efficiency is dependent on specific ion exchange interactions and therefore less consistent than RO for general conductivity removal.

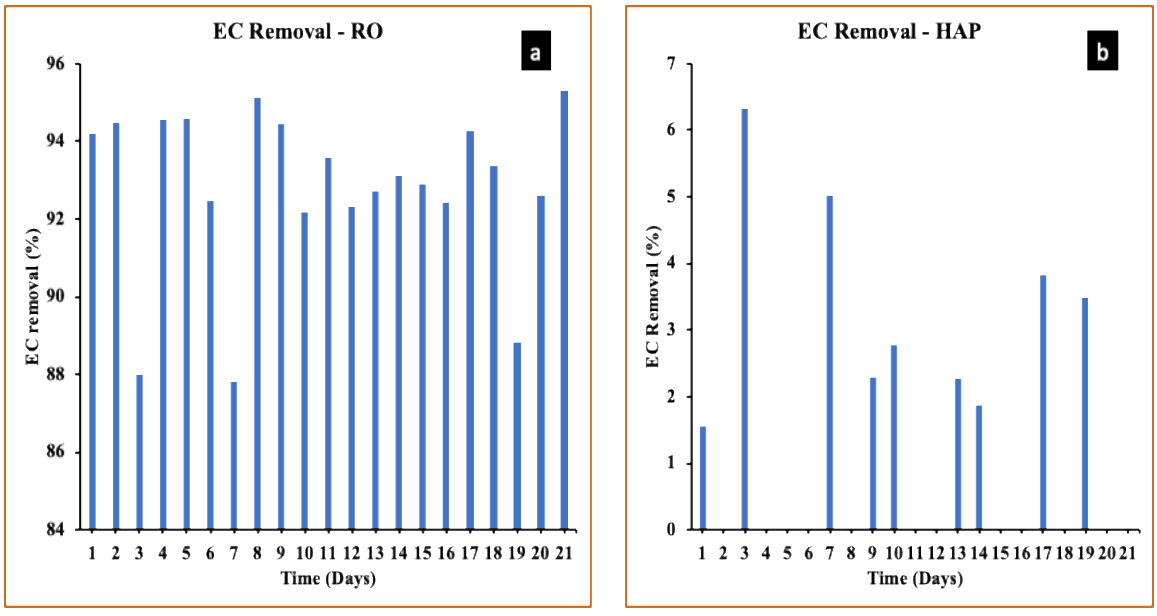

Figure 3: Electrical conductivity removal from a) RO and b) HAP treatment.

The results of turbidity removal from RO and HAP systems is shown in Figure 3. RO displayed highly effective removal, a removal of 70 % – 98.6 %, filtering out suspended particles and other impurities above 90 % in the course of 21 days as shown in Figure 4. Some samples shown near complete turbidity removal, making it

one of the most reliable methods for producing clear water. HAP, while effective may not match the removal efficiency of RO (Trikha, 2014). However, in this experiment, HAP was able to remove between 65 % to 80%. Due to the specificity of HAP, a hybrid system combining RO and HAP could improve efficiency by using HAP as a pre-treatment stage while optimizing cost and energy use.

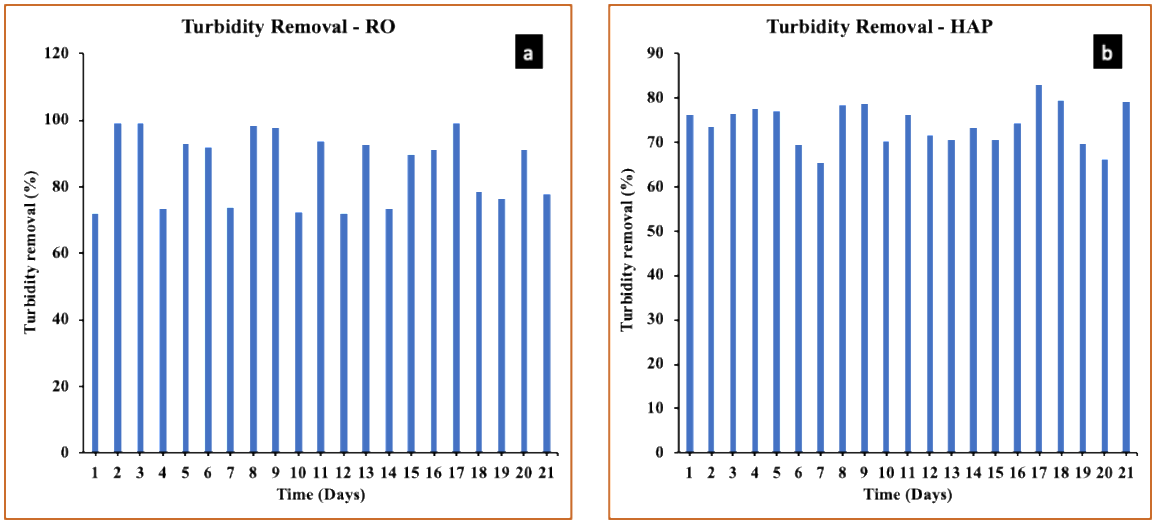

Figure 4: Turbidity removal from a) RO and b) HAP.

Fluoride removal

From Figure 5, the RO shows the removal efficiency between 96.05% up to 97.66% maximum. This implies that RO has greater fluoride removal efficiency. The mean fluoride and standard deviations of raw water were treated to a minimum of 1.5 mg/l, which is regarded as the maximum range of fluoride standard in water as recommended by WHO (WHO, 2011) and TBS (TBS, 2018). The study reveals that, the raw water from selected boreholes was at in unacceptable level since it was above 1.5 mg/l.

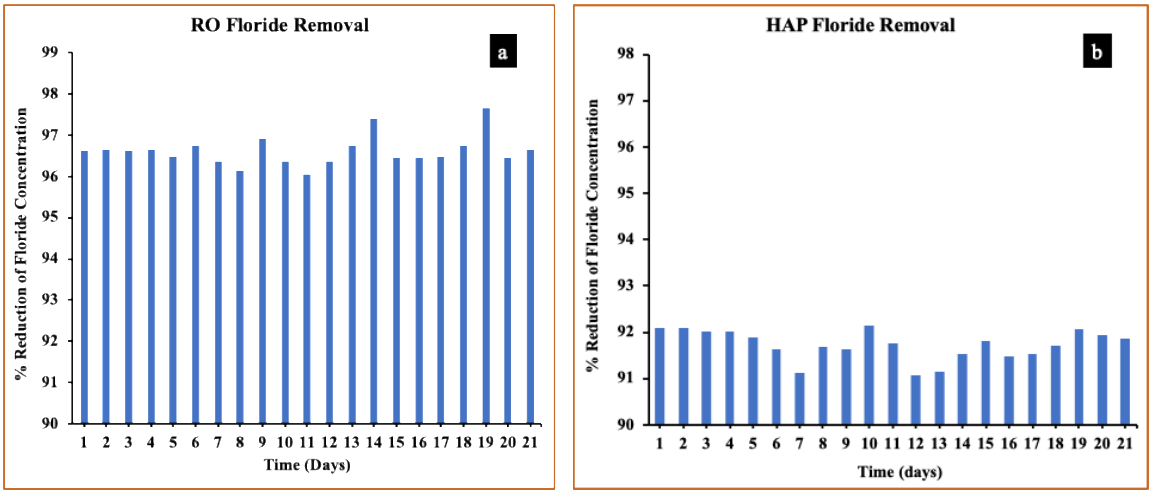

Figure 5: Fluoride removal from a) RO and b) HAP.

The Comparative Analysis in Terms of Water Quality and Energy

This study evaluated the defluoridation efficiency of Hydroxyapatite (HAP) and Reverse Osmosis (RO) technologies. Both methods effectively removed over 90% of excess fluoride from water. Specifically, HAP achieved a fluoride removal efficiency between 91.51% and 93.41%, while RO demonstrated superior

performance, removing 96.05% to 97.66% of fluoride. Despite its high efficiency, RO exhibited significant energy consumption, operating three pumps in series: a feed pump (8.5 kWh), a pressure pump (17.5 kWh), and dosing pumps (1.5 kWh), totalling 27.5 kWh, excluding cleaning-in-place (CIP) requirements. In contrast, HAP required only 2.5 kWh, making it a more energy-efficient alternative.

Additionally, RO resulted in substantial water loss, rejecting approximately 30% of raw water post-treatment, while HAP retained 99% of the input water. Furthermore, RO's CIP process used clean water, further contributing to water loss, whereas HAP utilized raw water during regeneration, minimizing waste.

Overall, while RO offers higher fluoride removal efficiency, its high energy demand and water loss present operational challenges. On the other hand, HAP provides a more sustainable solution, balancing efficiency with lower energy consumption and minimal water rejection.

A t-test at a 95% confidence level revealed a statistically significant difference ($p < 0.001$) in mean fluoride levels between HAP-treated water and RO-treated water. The mean fluoride level is higher in HAP-treated water compared to RO-treated water, with a confidence interval indicating that the true population mean difference falls within the reported range. The following Table 1 summarizes the noted differences between RO and HAP experiments.

Table 1: Noted differences between RO and HAP experiments

S/N	Reverse Osmosis (RO) experiment	HAP experiment
1	Fluoride removal up to 97.66%	Fluoride removal up to 93.41%.
2	High energy consumption (equals 55 kWh)	Low consumption of energy (equals 2.5 kWh)
3	High water loss (equals 30% of feed water)	No water loss
4	Use chemicals for pre- and post-treatment	No chemicals needed for production
5	Clean water is used for CIP	Raw water used for regeneration
6	Membranes are expensive	HAP media are cheaper than membrane

Water quality plays a crucial role in the efficiency of Reverse Osmosis (RO) and hydroxyapatite (HAP) processes, with various parameters influencing their performance. pH, affects membrane stability in RO, too high or too low, and you risk scaling or membrane degradation on the other hand while in HAP, it dictates how well adsorption and precipitation occur. Total Dissolved Solids (TDS) can be a challenge for both systems; in RO, high TDS increases osmotic pressure and promotes scaling, whereas in HAP, it can interfere with adsorption by introducing competing ions. Hardness, mainly from calcium and magnesium, tends to clog RO membranes, reducing their efficiency, while in HAP, it can aid in precipitation but might also lead to excess sludge build-up. Suspended solids and turbidity pose another issue, as they cause fouling in RO membranes and block adsorption sites in HAP, making pre-treatment necessary. Additionally, oxidants like chlorine can degrade RO membranes, while organic matter causes fouling in both processes. Keeping these parameters in check is essential for ensuring smooth operation and prolonging system lifespan. In this project, it is anticipated that these factors may have influenced the outcomes in both processes.

Comparative cost per unit of treated water

The cost of producing water using Reverse Osmosis (RO) was determined by dividing

the total operational expenses by the energy consumed or water produced. The system generates 6 m^3 of treated water every five minutes. The total monthly expenses include chemical costs (37,500,000 TZS), electricity (15,000,000 TZS), and labor costs for three workers, each earning 600,000 TZS per month for 8-hour shifts. This results in an hourly operational cost of 76,000 TZS, equating to a unit water production cost of 1,050 TZS per m^3.

The HAP treatment system operates with a single pump, consuming approximately 15 kWh to transport water from boreholes to storage and through the filtration vessel containing HAP media. The total daily operational cost is 145,000 TZS, covering gas procurement, electricity, and sodium hydroxide for regeneration. The unit water production cost is determined by dividing half-hourly expenses by the treated volume (6 m^3), resulting in 504 TZS per m^3.

The research highlights the pressing challenge of poor water quality and the increasing demand for clean water due to low production. This study suggested that the HAP treatment system is a practical and sustainable solution, offering effective fluoride removal while remaining affordable and energy-efficient, making it a viable choice for communities in need of clean and safe drinking water.

The results indicate that RO offers an effective solution by removing high fluoride concentrations, ensuring safe drinking water, but it requires substantial energy, regular membrane maintenance, and proper disposal of reject water, which can pose environmental challenges. On the other hand, HAP presents a cost-effective alternative, particularly suitable for rural communities, as it utilizes locally available materials and generates minimal waste. Integrating these technologies into Arusha's water management strategies can enhance access to fluoride-free water while promoting sustainable resource utilization. However, careful planning is needed to address operational costs, infrastructure requirements, and community adoption, ensuring long-term viability and environmental safety.

CONCLUSIONS AND RECOMMENDATIONS

The research work was conducted to compare the removal efficiencies of fluoride in water in Arusha City. Generally, the results suggested that HAP media can significantly reduce fluoride and conserve water. Based on the research findings the following specific conclusions were drawn.

(i) The major chemical composition of HAP is CaO, P_2O_5 and H_2O. The composition of these elements forms Hydroxyapatite, which is locally available in small quantities since they exist in animal bones.

(ii) The research work reveals, with a 95% confidence level, that the HAP proved to be useful for the removal of 93.41% of mean fluoride within 30 30-minute hydraulic retention time, but the solid waste produced during the HAP experiment seemed to be a challenge in handling it.

Experimental data revealed that RO lost 30% of the feed water that became reject water during the experiment. This means that the reverse osmosis process is losing 1.8 cubic meters for each 6 cubic meters that enters the reverse osmosis after each five (5) minutes. So, rejected water from Reverse Osmosis was a problem in this research

Based on the study findings, the following are recommended:

(i) Since the HAP media can be utilized in the removal of fluoride. The HAP could be up scaled to comply with the demand in large scale production. The HAP media are generated from animal bones, so for large scale production, it needs the traditional availability of HAP material

(ii) Further studies are suggested to assess the impact of waste generated by HAP media during

treatment process. Also, the ways and protection measures in handling fluorapatite should be addressed clearly.

(iii) Further research on the development of hybrid system of HAp-RO to optimize cost and maximize fluoride removal and sustainability.

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