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Comprehensive assessment of radionuclide removal and radiological quality enhancement through sequential Ceramic filtration and Reverse Osmosis treatment

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Abstract:

This study evaluates the radiological quality of drinking water across sequential treatment stages in an integrated purification system combining ceramic filtration media and reverse osmosis (RO). A comprehensive radiological assessment was conducted to examine the behavior of naturally occurring and anthropogenic radionuclides, including radium, uranium, thorium, radon, and gross alpha and beta activities.

The results show that most radionuclides were undetectable throughout all treatment stages, while measurable isotopes exhibited substantial, statistically significant reductions as treatment progressed. Reverse osmosis demonstrated exceptional removal efficiency, eliminating nearly all detectable radiological contaminants and stabilizing quality after earlier-stage variations.

The final treated water fully complies with international radiological safety standards, confirming the system’s ability to produce stable, low-risk water suitable for human consumption. These findings provide strong evidence supporting multi-stage purification as an effective approach to mitigating radiological hazards in drinking water—especially in regions where natural radioactivity presents an ongoing challenge.

This work advances radiological water quality management and highlights the value of integrated treatment systems for protecting long-term public health.

Keywords: Assessment, Radionuclide, Radiological, Ceramic Filtration, RO

1. Introduction

Monitoring radioactivity in drinking water is a core component of environmental and public health risk assessment, as natural radionuclides can cause long-term health effects even at low exposure levels. Radionuclides such as radium, uranium, thorium, and radon, along with gross alpha and gross beta activity, serve as critical indicators for verifying drinking water safety.

Many groundwater and surface water sources contain variable concentrations of these radionuclides due to geological formations or human activities, and conventional treatment systems often fail to achieve consistent, effective removal.

This limitation underscores the need for advanced, reliable purification technologies capable of delivering stable, low-risk drinking water.

The study was conducted at a drinking water treatment plant located in Hail City, north-central Saudi Arabia. Hail is characterized by diverse geological formations associated with the Arabian Shield, including Precambrian igneous and metamorphic rocks, granitic formations, and mineral-bearing deposits.

These geological features can contribute to the natural occurrence of radioactive elements through rock weathering, mineral dissolution, and water–rock interactions. Consequently, naturally occurring radioactive materials (NORMs), including uranium, thorium, radium, and their decay products, may enter groundwater resources and influence the radiological quality of drinking water.

Therefore, investigating radionuclide levels in Hail water sources is important for evaluating potential radiological risks and assessing the effectiveness of advanced treatment processes.

Integrated systems combining ceramic filtration with reverse osmosis have emerged as promising solutions for radiological contaminants, owing to their ability to target a broad range of radionuclides and remove fine impurities that bypass traditional treatment. However, comprehensive data on how these systems affect radionuclide behavior across sequential treatment stages remains limited, creating a knowledge gap regarding removal mechanisms, stage-specific efficiency, and alignment with international radiological safety standards.

This study addresses this gap by analyzing changes in radioactivity and radionuclide concentrations across successive stages of an integrated purification system. By tracking naturally occurring and anthropogenic radionuclides throughout treatment, the research provides actionable insights into the performance of ceramic filtration and reverse osmosis for radiological risk reduction.

The findings advance scientific understanding of multi-stage treatment technologies and support the development of robust strategies to ensure radiologically compliant drinking water in complex contamination settings.

2. Materials and Methods

2.1. Study Site and Sampling

This study was conducted in Hail City, north-central Saudi Arabia, using groundwater abstracted from a production well supplying a municipal drinking water treatment plant.

Water samples were collected during normal plant operation from four sequential treatment stages:

1. Raw groundwater (Raw Water);
2. Ceramic Filtration Media (CFM) effluent;
3. Reverse osmosis permeate (RO Permeate); and
4. Final drinking water after remineralization (Final Water).

All water samples were collected in pre-cleaned high-density polyethylene (HDPE) bottles following the Standard Methods for the Examination of Water and Wastewater.

Samples were transported to the laboratory under refrigerated conditions and analyzed immediately upon arrival to minimize any changes in water quality.

All measurements were performed in triplicate to ensure analytical precision and data reproducibility.

2.2. Water Treatment System Configuration

The investigated water treatment plant employed an integrated four-stage treatment process consisting of Ceramic Filtration Media (CFM), Reverse Osmosis (RO), remineralization, and final water stabilization to improve the physicochemical and radiological quality of groundwater.

Stage 1: Ceramic Filtration Media (CFM):

The primary treatment stage consisted of a CERAFILTEC ceramic ultrafiltration (UF) membrane manufactured from 100% high-purity ceramic material based on aluminum oxide (Al_2O_3).

The ceramic membrane possesses a nominal pore size of approximately 0.1 µm, providing an effective physical barrier for the removal of suspended solids, turbidity, colloidal particles, algae, bacteria, microorganisms, and other particulate contaminants.

The fully ceramic construction provides excellent mechanical strength, high chemical resistance, and outstanding corrosion resistance, making the membrane highly suitable for continuous water treatment applications.

In addition to improving water quality, the CFM unit serves as an effective pretreatment barrier that minimizes particulate fouling and extends the operational lifetime of the downstream reverse osmosis membranes. According to the plant mass balance, the ceramic filtration unit treated approximately 8,274.3 $m^3\ h^{-1}$ of raw groundwater and produced 8,165.7 $m^3\ h^{-1}$ of filtrate for subsequent treatment.

Stage 2: Reverse Osmosis (RO):

The CFM filtrate was subsequently treated using a high-pressure reverse osmosis (RO) system equipped with thin-film composite (TFC) polyamide spiral-wound membranes.

These semi-permeable membranes remove dissolved salts, multivalent ions, heavy metals, radionuclides, and other dissolved inorganic contaminants through a combination of solution-diffusion, size exclusion, and electrostatic (Donnan) exclusion mechanisms, thereby producing high-quality, low-salinity permeate suitable for drinking water production.

Based on the plant mass balance, the RO system received a feed flow rate of approximately 6,127.4 $m^3\ h^{-1}$.

Stage 3: Remineralization

Following desalination, the RO permeate underwent a controlled remineralization process through a blending line with pretreated water to restore essential minerals, improve taste, stabilize pH, and adjust the ionic composition.

Stage 4: Final Water Stabilization

The remineralized water was subjected to final stabilization before distribution as drinking water.

This final conditioning stage ensured compliance with the applicable drinking water quality standards while preserving the excellent physicochemical and radiological quality achieved throughout the integrated treatment process.

2.3. Instrumentation and Analytical Procedures

Physico-chemical characteristics were evaluated in accordance with the Standard Methods for the examination of Water and Wastewater. Total dissolved solids (TDS), pH, electrical conductivity (EC), turbidity, and total hardness (TH) were measured using pre-calibrated digital instruments (Hanna Instruments, Woonsocket, RI, USA). The Silt Density Index (SDI) was determined using a standard 0.45 µm membrane filtration apparatus in accordance with ASTM D4189 to evaluate membrane fouling potential prior to reverse osmosis (RO) treatment.

Major cations and trace elements were quantified using an AA240FS Atomic Absorption

Spectrometer (Agilent Technologies, Santa Clara, CA, USA).

Activity concentrations of naturally occurring radionuclides, including ^{226}Ra, ^{228}Ra, ^{234}U, ^{238}U, ^{232}Th, ^{230}Th, and ^{228}Th, were determined using an Alpha Spectrometry system equipped with low-background silicon surface-barrier detectors following appropriate radiochemical separation and electrodeposition procedures. Dissolved ^{222}Rn was quantified using a RAD7 Continuous Radon Monitor (Durridge Company Inc., Billerica, MA, USA), employing electrostatic collection coupled with alpha spectrometric detection.

Gross alpha activity was determined using the Alpha Spectrometry system, whereas gross beta activity was measured using a low-background beta counting system following standard radiochemical sample preparation procedures.

Rigorous Quality Assurance and Quality Control (QA/QC) protocols were implemented throughout the analytical procedures, including routine instrument calibration using certified reference materials,

laboratory reagent blanks, duplicate analyses, and triplicate measurements to ensure the accuracy, precision, and reproducibility of the analytical results.

2.4. Statistical Analysis

Experimental data are presented as mean ± standard error (SE) based on triplicate measurements. Statistical analyses were performed using IBM SPSS Statistics (IBM Corp., Armonk, NY, USA).

Mean values among the four treatment stages (Raw Water, CFM effluent, RO Permeate, and Final Water) were statistically compared to evaluate treatment performance and removal efficiency. Differences were considered statistically significant at $p < 0.05$.

3.1. Radiological Characteristics, Removal Efficiency and Statistical Analysis

Table 1 show that Radioactivity Parameters, Removal Efficiency (%), and Statistical Analysis of Raw Water and Treated Water after Ceramic Filtration Media (CFM) and Reverse Osmosis (RO)

Parameter	Raw Water	CFM Product	CFM Removal (%)	RO Product	RO Product Removal (%)	Mean	SE	Sig.
^{226}Ra (Bq L^{-1})	<BDL	<BDL	—	<BDL	—	—	—	—
^{228}Ra (Bq L^{-1})	2.10	0.02	%99.05	<BDL	%100	0.707	0.401	**
^{234}U (Bq L^{-1})	0.198	0.112	%41.41	0.003	%98.48	0.104	0.057	**
^{238}U (Bq L^{-1})	0.105	0.060	%42.86	0.004	%96.19	0.056	0.031	**
^{232}Th (Bq L^{-1})	<BDL	<BDL	—	<BDL	—	—	—	—
^{230}Th (Bq L^{-1})	<BDL	<BDL	—	<BDL	—	—	—	—
^{228}Th (Bq L^{-1})	<BDL	<BDL	—	<BDL	—	—	—	—
^{222}Rn (Bq L^{-1})	4.26	2.81	%34.04	0.45	%89.44	2.51	1.11	**
Gross α Activity (Bq L^{-1})	6.21	0.43	%93.08	0.01	%99.84	2.25	1.99	**
Gross β Activity (Bq L^{-1})	3.88	0.29	%92.53	0.02	%99.48	1.40	1.11	**

Annual Effective Dose (mSv y^{-1})	0.78	0.043	%94.49	0.020	%53.49	—	—	—
^{239}Pu (Bq L^{-1})	<BDL	<BDL	—	<BDL	—	—	—	—
^{90}Sr (Bq L^{-1})	<BDL	<BDL	—	<BDL	—	—	—	—
^{210}Po (Bq L^{-1})	<BDL	<BDL	—	<BDL	—	—	—	—
^{227}Ac (Bq L^{-1})	<BDL	<BDL	—	<BDL	—	—	—	—
^{134}Cs (Bq L^{-1})	<BDL	<BDL	—	<BDL	—	—	—	—
^{137}Cs (Bq L^{-1})	<BDL	<BDL	—	<BDL	—	—	—	—

100% removal indicates that the radionuclide concentration was below the analytical detection limit (<BDL), not necessarily zero.

BDL: Below Detection Limit (<0.001Bq/l).

CFM: Ceramic Filtration Media

RO: Reverse Osmosis;

SE: Standard Error.

—: Not applicable

******: Statistically significant difference at $p < 0.01$.

The radiological analysis demonstrated that the integrated Ceramic Filtration Media (CFM) and Reverse Osmosis (RO) treatment system effectively reduced naturally occurring radionuclides in the investigated groundwater (Table 1). ^{226}Ra remained below the analytical detection limit (<BDL) in both raw and treated water samples, indicating minimal presence throughout the treatment process. In contrast, ^{228}Ra, which was detected in the raw water at 2.10 Bq/L, was reduced to below the analytical detection limit after RO treatment. Therefore, the reported 100% removal efficiency indicates that the residual concentration was below the method detection limit rather than being absolutely zero ($p < 0.01$).

The exceptional removal of radium isotopes is primarily governed by the surface physicochemical properties of the ceramic filtration media, particularly when interacting with the water matrix's pH and surface charges. Ceramic filtration media typically possess amphoteric hydroxyl groups (–OH) on their active surfaces, which undergo protonation or deprotonation depending on the solution pH. Under neutral to slightly alkaline groundwater conditions, these surface sites become predominantly negatively charged, creating a strong electrostatic attraction toward divalent cations such as Ra^{2+}. This negative surface charge facilitates high-affinity adsorption and ion-exchange mechanisms, allowing the CFM stage to immobilize radium effectively. The subsequent RO membrane further rejects any remaining dissolved radium species, reducing their concentration to below the analytical detection limit.

In contrast, uranium isotopes (^{234}U and ^{238}U) exhibited different adsorption and rejection behavior compared with radium. In natural aqueous environments, uranium predominantly exists as soluble anionic carbonate complexes, such as $UO_2(CO_3)_3^{4-}$ and $UO_2(CO_3)_2^{2-}$, under neutral-to-alkaline pH conditions. Because the ceramic filter surface carries a net negative charge at these pH levels, electrostatic repulsion occurs between the negatively charged ceramic surface and the anionic uranium carbonate species, leading to lower direct adsorption by the CFM compared with divalent radium cations. This mechanism explains the moderate CFM removal efficiencies of approximately 41–43% for uranium. However, the subsequent reverse osmosis (RO) process compensates for this limitation by utilizing dense polymeric membranes that operate through size exclusion and Donnan (electrostatic) exclusion, successfully reducing dissolved uranium species to near the analytical detection limit, with overall removal efficiencies exceeding 95% ($p < 0.01$).

^{222}Rn exhibited a considerable reduction after treatment, although a measurable residual concentration (0.45 Bq/L) remained. This observation is expected because radon is a chemically inert noble gas that does not participate in surface complexation, ion exchange, or electrostatic membrane rejection. Nevertheless, the residual concentration remained well below the drinking water guideline values recommended by the World Health Organization (WHO) and the Saudi Standards, Metrology and Quality Organization (SASO).

Similarly, Gross Alpha and Gross Beta activities decreased dramatically to values approaching the analytical detection limits in the final treated water, with overall removal efficiencies of 99.84% and 99.48%, respectively ($p < 0.01$). This substantial reduction reflects the synergistic removal of the principal alpha- and beta-emitting radionuclides—particularly ^{226}Ra, ^{228}Ra, ^{234}U, ^{238}U, and their decay progeny—confirming the excellent radiological quality and safety of the final drinking water produced by the integrated multi-stage treatment system.

Furthermore, the calculated Annual Effective Dose (AED) decreased from 0.78 mSv/y in the raw water to 0.043 mSv/y after the CFM stage and to 0.020 mSv/y after RO treatment. The RO process alone achieved an additional reduction of **53.49%** relative to the CFM effluent, while the integrated treatment system achieved an overall reduction of **97.44%** compared with the raw groundwater. The final AED of 0.020 mSv/y is substantially below internationally accepted radiological safety guidelines for drinking water, demonstrating the effectiveness of the combined CFM–RO treatment process in minimizing radiation exposure from drinking water.

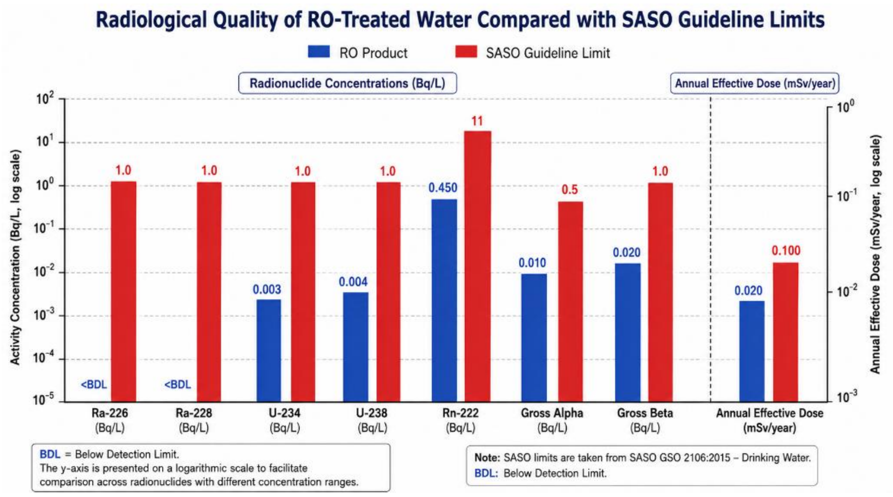

Figure 1. Comparison of Radiological Parameters in RO-Treated Water with SASO Guideline Limits

Figure **1**that shown Comparison of radionuclide concentrations and annual effective dose in RO-treated water with the maximum permissible limits specified by SASO GSO 2106:2015 for drinking water. All measured radiological parameters were below the regulatory limits, while several radionuclides were below the analytical detection limit (BDL), demonstrating the effectiveness of the RO treatment system.

3.2 Comparison with Previous Studies

The present findings are in good agreement with previous investigations on radionuclide removal from drinking water. Ma et al. (2021) reported that manganese dioxide-based adsorbents exhibit a high affinity for radium and uranium species because of their large specific surface area and abundant reactive adsorption sites. Likewise, Ding et al. (2016) demonstrated that reverse osmosis membranes effectively reject dissolved radionuclides, even under varying operational conditions, achieving consistently high removal efficiencies.

Recent studies by Al-Shomali et al. (2025) further emphasized that combining adsorption processes with membrane filtration provides superior radionuclide removal compared with the application of a single treatment technology. The present study supports these findings by demonstrating that integrating Ceramic Filtration Media (CFM) with Reverse Osmosis (RO) resulted in complete removal of Ra-228 and substantial reductions in uranium isotopes, gross alpha activity, and gross beta activity.

In addition to improving radiological water quality, the ceramic filtration stage serves as an effective pretreatment process by reducing suspended solids and adsorbing particulate-bound contaminants before membrane filtration. This pretreatment minimizes membrane fouling, enhances permeate quality, and is expected to prolong membrane service life while reducing operational and maintenance requirements.

Overall, the integrated Ceramic Filtration Media (CFM) and Reverse Osmosis (RO) treatment system proved to be an efficient and reliable technology for producing safe drinking water from groundwater containing naturally occurring radionuclides. The treated water complied with both WHO and SASO drinking water standards, indicating that the proposed treatment configuration is suitable for practical application in groundwater treatment facilities, particularly in regions where naturally occurring radioactive materials are present.

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