JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Evaluation of Physicochemical and Radiological Transformations in Drinking Water Across Multi-Stage Treatment Processes

Nosuba Hatim Omer[1], Prof.Yasir A. Mohamed[1],Dr.Elrafie A. A.Allah[1]

Department of Chemical Engineering, Faculty of Engineering, University of El Imam El Mahdi, Kosti, Sudan

Abstract

This study evaluated the performance of a full-scale multi-stage drinking water treatment system for improving the physicochemical and radiological quality of groundwater in Hail City, Saudi Arabia. The treatment train consisted of aeration, pH adjustment, hydrated manganese oxide (HMO)-coated ceramic filtration (CFM), reverse osmosis (RO), and post-treatment remineralization through a blending line.

Water samples were collected from the raw groundwater, CFM-treated water, and RO-treated water in triplicate. Physicochemical parameters, major ions, naturally occurring radionuclides, and dissolved radon were analyzed using standard analytical methods, and statistical differences among treatment stages were evaluated using one-way analysis of variance (ANOVA).

The integrated treatment system significantly improved water quality by reducing total dissolved solids, hardness, major ions, trace metals, and naturally occurring radionuclides. In the final drinking water, total dissolved solids (TDS) and Ra-226 concentrations were reduced by 76.07% and 97.85%, respectively, while gross alpha activity, gross beta activity, and the annual effective dose also decreased markedly. Most investigated parameters showed statistically significant differences among treatment stages ($p < 0.05$).

The final drinking water complied with the Saudi Standards, Metrology and Quality Organization (SASO) requirements and relevant international drinking water guidelines for both physicochemical and radiological quality. These findings demonstrate that the combined HMO-coated ceramic filtration and reverse osmosis system provides an efficient and reliable solution for producing safe drinking water and minimizing exposure to naturally occurring radioactive contaminants in groundwater-dependent arid regions

Keywords: Evaluation, Physicochemical, Radiological, Drinking Water, Treatment

1. Introduction

Ensuring access to safe drinking water remains one of the most important global public health priorities. In addition to conventional physicochemical contaminants, groundwater may contain naturally occurring radionuclides, particularly radium isotopes (Ra-226 and Ra-228) and dissolved radon (Rn-222), which may increase long-term health risks when present at elevated concentrations. Consequently, national and international drinking water regulations have become increasingly stringent, requiring the implementation of advanced treatment technologies capable of simultaneously removing both chemical and radiological contaminants.

Groundwater is an essential source of drinking water in many arid and semi-arid regions, including Saudi Arabia. However, groundwater quality is often influenced by local geological formations, resulting in elevated concentrations of dissolved salts, hardness, trace elements, and naturally occurring radioactive materials (NORM). These contaminants may

adversely affect both water quality and public health, emphasizing the need for efficient and reliable treatment technologies.

Reverse osmosis (RO) has been widely recognized as one of the most effective technologies for reducing salinity and removing dissolved contaminants. Nevertheless, appropriate pretreatment remains essential for minimizing membrane fouling, improving operational stability, and enhancing the overall performance of RO systems. Among the available pretreatment technologies, hydrated manganese oxide (HMO)-coated ceramic filtration has attracted considerable attention because of its high adsorption capacity and selectivity for radium removal while simultaneously reducing suspended particles and improving feed water quality prior to membrane treatment.

In the present treatment system, raw groundwater first underwent aeration and pH adjustment to optimize the subsequent treatment processes. The preconditioned water was then passed through a standalone HMO-coated ceramic filtration (CFM) unit, where hydrated manganese oxide selectively adsorbed dissolved radium while providing additional removal of fine suspended particles. The pretreated water subsequently entered the reverse osmosis (RO) system for the removal of dissolved salts, major ions, trace metals, residual radionuclides, and dissolved radon. Finally, the RO permeate was remineralized through a controlled blending process to restore essential minerals and produce drinking water with acceptable physicochemical characteristics and consumer acceptability.

Although numerous studies have evaluated either reverse osmosis performance or radionuclide removal individually, relatively few investigations have simultaneously assessed physicochemical quality, naturally occurring radionuclides, dissolved radon, and treatment efficiency using an integrated HMO-coated ceramic filtration and reverse osmosis system operating under full-scale conditions. Furthermore, limited information is available regarding the combined radiological and physicochemical performance of such systems treating groundwater in Saudi Arabia. Therefore, a comprehensive evaluation of integrated treatment technologies remains necessary to support the production of safe drinking water and optimize treatment performance.Accordingly, this study aimed to:

evaluate the removal efficiency of physicochemical parameters throughout the different treatment stages;

assess the removal of naturally occurring radionuclides, including Ra-226,Ra-228, U-234, U-238,Th-232,Th-230, Th-228, and dissolved Rn-222;

compare the quality of the RO-treated water with the requirements of the Saudi Standards, Metrology and Quality Organization (SASO) and the World Health Organization (WHO) drinking water guidelines; and statistically evaluate the performance of the integrated treatment system using one-way analysis of variance (ANOVA).

This study provides a comprehensive assessment of the physicochemical and radiological performance of an integrated HMO-coated ceramic filtration and reverse osmosis treatment system operating in a full-scale drinking water treatment plant. The findings contribute to the understanding of advanced groundwater treatment technologies and provide scientific evidence supporting the production of safe drinking water while reducing naturally occurring radioactive contaminants to levels compliant with national and international drinking water standards.

2. Materials and Methods

2.1. Study Site

This study was conducted in Hail City, Saudi Arabia, where groundwater represents the primary source of drinking water. The hydrogeological characteristics of the region are influenced by sedimentary and crystalline rock formations that may contribute to the occurrence of naturally occurring radioactive materials (NORM), particularly radium and uranium isotopes. Groundwater used in this study was obtained from a single production well supplying a full-scale drinking water treatment plant. The treatment plant employed a multi-stage treatment system consisting of aeration, pH adjustment, a standalone hydrated manganese oxide (HMO)-coated ceramic filtration (CFM) unit, chemical conditioning, reverse osmosis (RO), and final blending (remineralization) to improve the physicochemical and radiological quality of groundwater prior to distribution.

2.2. Water Sampling

Water samples were collected from three representative sampling points throughout the treatment process: (i) raw groundwater before treatment, (ii) water after the HMO-coated ceramic filtration (CFM) unit, and (iii) reverse osmosis (RO) permeate. Each sample was collected in triplicate using pre-cleaned polyethylene bottles following standard water sampling procedures. Sampling was conducted during normal plant operating conditions to ensure representative water quality throughout the treatment process. Samples were transported to the laboratory under appropriate preservation conditions and analyzed within the recommended holding times. Samples intended for radiological analysis were

collected, preserved, and handled according to standard analytical protocols to prevent contamination and minimize radionuclide losses.

2.3. Water Treatment Process

The drinking water treatment plant employed a multi-stage treatment process designed to improve both the physicochemical and radiological quality of groundwater prior to distribution. The treatment train consisted of aeration, pH adjustment, HMO-coated ceramic filtration (CFM), chemical conditioning, reverse osmosis (RO), and final blending (remineralization).

2.3.1. Aeration and pH Adjustment

Raw groundwater was initially subjected to aeration to improve water quality prior to treatment. Following aeration, the pH of the water was adjusted to optimize the performance of the subsequent treatment processes, particularly the HMO-coated ceramic filtration unit and the reverse osmosis system.

2.3.2. HMO-Coated Ceramic Filtration (CFM)

Following pH adjustment, the groundwater passed through a standalone hydrated manganese oxide (HMO)-coated ceramic filtration (CFM) unit. The hydrated manganese oxide coating exhibited a high affinity for the adsorption of naturally occurring radionuclides, particularly radium isotopes, while simultaneously reducing residual suspended particles. This pretreatment stage improved the feed water quality and reduced the contaminant load entering the reverse osmosis system.

2.3.3. Chemical Conditioning

Prior to reverse osmosis, the pretreated water underwent chemical conditioning to optimize membrane performance and minimize mineral scaling and membrane fouling. Appropriate conditioning was applied to maintain stable operating conditions and enhance the efficiency of the subsequent membrane treatment process.

2.3.4. Reverse Osmosis (RO)

The conditioned water was treated using a reverse osmosis membrane system to remove dissolved salts, hardness, major ions, trace metals, naturally occurring radionuclides, and dissolved radon. Reverse osmosis served as the principal desalination and purification stage, producing high-quality permeate with substantially reduced physicochemical and radiological contaminants.

2.3.5. Final Blending (Remineralization)

Following reverse osmosis, the treated water underwent controlled blending (remineralization) to restore essential minerals and improve the physicochemical characteristics, stability, and consumer acceptability of the drinking water prior to distribution.

2.4. Instrumentation and Analytical Methods

The physicochemical and radiological characteristics of the collected water samples were determined using calibrated analytical instruments following standardized analytical procedures and the manufacturers' operating instructions. The analytical results were evaluated in accordance with the World Health Organization (WHO) Guidelines for Drinking-water Quality and the Saudi Standards, Metrology and Quality Organization (SASO) drinking water standards.

Physicochemical parameters, including pH, total dissolved solids (TDS), turbidity, and total hardness, were measured using calibrated laboratory instruments. Total hardness was determined using the ethylenediaminetetraacetic acid (EDTA) titrimetric method. The Silt Density Index (SDI) was determined using a standard SDI test apparatus equipped with a 0.45-µm membrane filter.

Major ions and trace metals were determined using an Atomic Absorption Spectrometer (AAS) according to the manufacturer's operating procedures. Activity concentrations of naturally occurring radionuclides, including Ra-226, Ra-228, U-234, U-238, Th-232, Th-230, and Th-228, were determined using a Polimaster PM1401K portable radiation spectrometer (Polimaster, Minsk, Belarus). Dissolved radon (Rn-222) concentrations were measured using a RAD7 continuous radon monitor (Durridge Company Inc., Billerica, MA, USA).

Quality assurance and quality control (QA/QC) procedures included routine instrument calibration, blank sample analysis, and triplicate measurements to ensure the accuracy, precision, and reproducibility of the analytical results.

2.5. Statistical Analysis

All analyses were performed in triplicate, and the results are expressed as mean ± standard error (SE). Statistical analyses were performed using IBM SPSS Statistics (IBM Corp., Armonk, NY, USA). Differences among the three sampling stages (raw groundwater, HMO-coated ceramic filtration (CFM)-treated water, and reverse osmosis (RO)-treated water) were evaluated using one-way analysis of variance (ANOVA). Statistical significance was considered at $p < 0.05$. The statistical analysis was conducted to evaluate the effectiveness of the treatment process in improving the physicochemical and radiological quality of groundwater and to determine whether the observed differences among the sampling stages were statistically significant.

3. Results and Discussion

3.1 Physicochemical and Radiological Changes Across Treatment Stages

Table 1 show that changes in the Physicochemical and Radiological Properties of Water During Different Treatment Stages and Their Statistical Significance:

Parameter	Raw Water (Mean ± SE)	CFM Product (Mean ± SE)	RO Permeate (Mean ± SE)	Final Drinking Water (Mean ± SE)	Sig.
TDS (mg/L)	775.5 ± 0.17	747.9 ± 0.12	58.8 ± 0.12	185.6 ± 0.12	**
pH	7.6 ± 0.12	7.4 ± 0.06	5.0 ± 0.06	8.1 ± 0.06	NS
^{226}Ra (pCi/L)	60.0 ± 0.12	3.9 ± 0.06	0.18 ± 0.006	1.29 ± 0.006	**
^{222}Rn (pCi/L)	810.0 ± 0.12	3.9 ± 0.06	4.0 ± 0.06	4.2 ± 0.06	**
Fe (mg/L)	0.20 ± 0.006	0.001 ± 0.0006	0.00 ± 0.00	0.00 ± 0.00	*
Mn (mg/L)	0.01 ± 0.006	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	*
Ca (mg/L)	97.5 ± 0.12	94.0 ± 0.12	3.9 ± 0.06	20.6 ± 0.12	**
Mg (mg/L)	12.7 ± 0.12	10.01 ± 0.01	0.5 ± 0.06	2.7 ± 0.06	**
Na (mg/L)	130.8 ± 0.12	94.7 ± 0.12	18.43 ± 0.012	33.9 ± 0.12	**
Cl (mg/L)	241.1 ± 0.12	112.1 ± 0.12	24.7 ± 0.12	58.5 ± 0.12	**
SO_4 (mg/L)	116.2 ± 0.12	88.7 ± 0.12	10.6 ± 0.12	25.1 ± 0.12	**

Parameter	Raw Water (Mean ± SE)	CFM Product (Mean ± SE)	RO Permeate (Mean ± SE)	Final Drinking Water (Mean ± SE)	Sig.
NO_3 (mg/L)	11.3 ± 0.12	10.9 ± 0.12	4.0 ± 0.06	5.1 ± 0.06	*
Total Hardness (mg/L)	295 ± 0.58	137.8 ± 0.12	12.0 ± 0.58	62.0 ± 0.58	**

Note:

*** = Highly significant at $P \leq 0.01$;*

* = Significant at $P \leq 0.05$;*

***SE** = Standard Error;*

***Sig.** = Significance level.*

NS = not significant

The treatment system demonstrated a substantial improvement in both the physicochemical and radiological quality of groundwater through the sequential application of the HMO-coated ceramic filtration (CFM) unit, reverse osmosis (RO), and post-treatment remineralization. The significant differences observed for most parameters ($P \leq 0.01$) indicate that the treatment process effectively modified water quality characteristics while producing water suitable for drinking purposes.

The total dissolved solids (TDS) concentration decreased from 775.5 ± 0.17 mg/L in the raw groundwater to 58.8 ± 0.12 mg/L after RO treatment, representing efficient desalination by the RO membrane. Following remineralization, TDS increased to 185.6 ± 0.12 mg/L, reflecting the controlled addition of essential minerals to improve taste, stability, and corrosivity. The final TDS remained well below the recommended drinking-water limits, indicating successful optimization of mineral composition.

The pH decreased from 7.6 ± 0.12 in raw water to 5.0 ± 0.06 after RO treatment because the removal of dissolved bicarbonates and alkalinity reduces the buffering capacity of permeate water. Following remineralization, the pH increased to 8.1 ± 0.06, which falls within the recommended drinking-water range and demonstrates the effectiveness of the post-treatment stabilization process.

Radiological parameters exhibited the greatest improvements. The concentration of ^{226}Ra decreased from 60.0 ± 0.12 pCi/L in raw groundwater to 3.9 ± 0.06 pCi/L after CFM treatment, indicating the high adsorption affinity of hydrated manganese oxide toward divalent radium ions. Further reduction to 0.18 ± 0.006 pCi/L after RO confirms the high rejection efficiency of membrane separation. The slight increase to 1.29 ± 0.006 pCi/L in the final drinking water is attributed to the remineralization stage or blending process; however, the concentration remained well below international drinking-water guideline values.

Similarly, ^{222}Rn activity decreased dramatically from 810.0 ± 0.12 pCi/L in raw groundwater to approximately 4 pCi/L after treatment. This remarkable reduction can be attributed to the combined effects of adsorption, membrane separation, and radon degassing during water processing. The residual radon concentration in the final drinking water was extremely low, demonstrating excellent radiological protection for consumers.

The HMO-coated ceramic filtration unit also effectively removed dissolved iron and manganese. Iron concentration decreased from 0.20 ± 0.006 mg/L to 0.001 ± 0.0006 mg/L, while manganese became below the analytical detection limit after treatment. These results confirm the strong adsorption capacity of hydrated manganese oxide for transition metals and support previous studies describing HMO as an efficient sorbent for both heavy metals and radionuclides.

Major cations and hardness exhibited trends characteristic of RO treatment. Calcium decreased from 97.5 ± 0.12 mg/L to 3.9 ± 0.06 mg/L, magnesium from 12.7 ± 0.12 mg/L to 0.5 ± 0.06 mg/L, and total hardness from 295 ± 0.58 ppm to 12 ± 0.58 ppm after RO. Controlled remineralization subsequently increased calcium to 20.6 ± 0.12 mg/L, magnesium to 2.7 ±

0.06 mg/L, and total hardness to 62 ± 0.58 ppm, producing water with balanced mineral content while maintaining excellent aesthetic and operational quality.

Likewise, sodium, chloride, sulfate, and nitrate concentrations decreased considerably following membrane treatment, confirming the high ion rejection performance of the RO system. Moderate increases observed after remineralization were expected because mineral addition is essential to improve water stability and palatability. Nevertheless, all measured concentrations remained well within recommended drinking-water standards.

Overall, the combined CFM–RO treatment system followed by controlled remineralization achieved excellent removal of radionuclides, dissolved salts, and inorganic contaminants while restoring appropriate mineral composition for drinking water. These findings demonstrate that the integrated treatment process provides an effective and reliable approach for producing safe drinking water from groundwater containing elevated natural radioactivity and dissolved minerals.

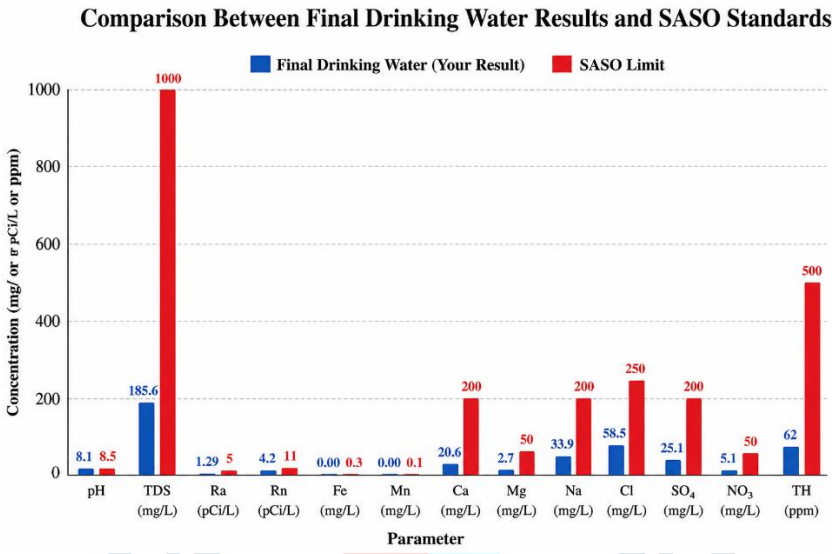

Figure 1show that comparison of the final drinking water quality parameters with the maximum permissible limits specified by SASO drinking water standards.

References

Al-Shomali, Z., Pereira, A., Marques, A. C., & Dinis, M. D. L. (2025). State-of-the-art review on removal of naturally occurring radioactive materials in water. International Journal of Environmental Research and Public Health, 22(5), 727. https://doi.org/10.3390/ijerph22050727

Ighalo, J. O., Chen, Z., Ohoro, C. R., Oniye, M., Igwegbe, C. A., Elimhingbovo, I., Khongthaw, B., Dulta, K., Yap, P.-S., & Anastopoulos, I. (2024). A review of remediation technologies for uranium-contaminated water. Chemosphere, 352, 141322. https://doi.org/10.1016/j.chemosphere.2024.141322

Ma, J., Wang, C., Qiu, M., Wang, J., & Wang, X. (2021). Removal of radionuclides from aqueous solution by manganese dioxide-based nanomaterials and mechanism research: A review. ACS ES&T Engineering, 1(4), 685–705. https://doi.org/10.1021/acsestengg.0c00268

Montgomery, D. C. (2019). Design and analysis of experiments (10th ed.). Wiley.

Saudi Standards, Metrology and Quality Organization. (2020). Unbottled drinking water (SASO 409:2020). Saudi Standards, Metrology and Quality Organization.

Sharma, S., Sharma, V., Mittal, A., Das, D. K., Sethi, S., Yadav, S., Vallamkonda, B., & Vashistha, V. K. (2024). Radioactive elements in wastewater and potable water: Sources, effects, and methods of analysis and removal. Water Environment Research, 96(8), e11106. https://doi.org/10.1002/wer.11106

U.S. Environmental Protection Agency. (2025). Overview of drinking water treatment technologies. https://www.epa.gov/sdwa/overview-drinking-water-treatment-technologies

U.S. Environmental Protection Agency. (2025). TENORM: Drinking water treatment residuals. https://www.epa.gov/radiation/technologically-enhanced-naturally-occurring-radioactive-materials-tenorm

Vengosh, A., Coyte, R. M., Podgorski, J., & Johnson, T. M. (2022). A critical review on the occurrence and distribution of uranium- and thorium-decay nuclides and their effect on groundwater quality. Science of the Total Environment, 808, 151914. https://doi.org/10.1016/j.scitotenv.2021.151914

World Health Organization. (2022). Guidelines for drinking-water quality (4th ed., incorporating the first and second addenda). World Health Organization. https://www.who.int/publications/i/item/9789240045064