



Journal of University Studies for Inclusive Research

Vol.2, Issue 51 (2026), 158173- 158183

USRIJ Pvt. Ltd

Reverse Osmosis Unit Design

Anwar Elhaj Eluass Elrayah ¹, Yassen Mohamed Musa Saleh ²

¹ University of Gezira, Sudan

² University of Kordofan, Sudan

Abstract

Groundwater represents the main source of drinking water in the Al-Butana region of central Sudan; however, elevated salinity and mineral content limit its direct use. This study presents the design and performance evaluation of a groundwater reverse osmosis (RO) unit with a production capacity of 705.8 m³/day, operating for 8 hours per day, to supply potable water for approximately 6,000 inhabitants. The system design was based on detailed physicochemical, heavy metal, and microbiological analyses of raw groundwater. Results indicate that the proposed RO system achieved a total dissolved solids (TDS) reduction from 1000–1500 mg/L to 150–200 mg/L, with significant removal of hardness, turbidity, heavy metals, and complete elimination of microbial indicators. The treated water complies with Sudanese Standards and Metrology Organization (SSMO) and World Health Organization (WHO) guidelines. The study confirms the suitability of reverse osmosis technology for medium-scale groundwater desalination in semi-arid regions.

Keywords: Groundwater desalination; Reverse osmosis; System design; Water treatment; Sudan.

1 Introduction

Reverse osmosis (RO) technology has become increasingly prominent due to its growing popularity and extensive application in the desalination industry (B. Penate & L. Garcia-Rodriguez, 2012), (H. Hyung, & J.H. Kim, 2006) This technology relies on semi-permeable membranes specifically designed to remove organic chemicals, proteins, and ions from

water sources (D.E. Sachit, & J.N. Veenstra, 2014) RO offers several advantages, including a compact footprint, efficient design, and automated process control features (P.-K. Park, et al., 2012) Moreover, compared to conventional thermal desalination methods such as multi-stage flashing (MSF) and multi-effect distillation (MED), RO systems require significantly less energy, making them a more energy-efficient solution (C. Fritzmann, et al., 2007; Mingheng Li,, 2011; Koussai Quteishat, et al., 2003; Baltasar Peñate & Lourdes García-Rodríguez, 2012). For the treatment of brackish water, RO is considered one of the most widely adopted technologies, particularly with low-energy brackish water reverse osmosis (BWRO) membranes (Mohammad A.K. Al-Sofi, et al., 2000). RO systems can achieve high salt rejection efficiencies, reaching up to 99.8% for seawater and exceeding 99% for brackish water applications (David A. Ladner,, et al., 2010) 490–499.).The concept of osmosis, a physical process that has been understood for many years (T.Y. Cath, A.E. Childress, & M. Elimelech, 2006),is fundamental to RO technology. Osmosis refers to the spontaneous movement of water molecules from a region of lower solute concentration (and thus lower osmotic pressure) to a region of higher solute concentration (higher osmotic pressure) through a semi-permeable membrane (Muhammad Qasim, et al., 2019). The membrane allows only water molecules to pass through while rejecting solutes

1.1 Objectives

1. To evaluate the physicochemical and microbiological quality of raw and treated water against WHO and SSMO standards.
2. To enhance water treatment efficiency through optimized pretreatment and multistage filtration processes.
3. To minimize energy consumption and operational cost using integrated energy recovery systems

1.2 Statement of Problem

1. Groundwater in the Al-Butana region exhibits elevated levels of salinity and hardness, rendering it unsuitable for direct human consumption without prior treatment.
2. The lack of centralized water treatment infrastructure in the Al-Butana area limits access to safe and reliable drinking water for rural communities.
3. The accumulation of suspended solids and scale formation on reverse osmosis membranes significantly reduces system performance and shortens membrane lifespan.

2 Literature Review

(Kensara & et al, 2019) addressed water scarcity in western Saudi Arabia, where conventional desalination plants rely on fossil fuels, causing high costs and environmental concerns. The study aimed to redesign an existing reverse osmosis (RO) plant to be fully powered by solar photovoltaic (PV) energy, enhancing sustainability, reducing operational costs, and ensuring energy independence. Using an Excel-based mathematical model, the

study simulated PV integration with the RO plant, considering solar parameters (time, angles, radiation) and plant operational data (pumps, energy recovery devices) to estimate daily energy demand of 757,000 Wh. The proposed design included 4,130 PV panels (400 W each) and ~13,865 batteries for continuous operation. Results showed the PV-RO system could fully meet the plant's energy needs, producing up to 18 million Wh/day, confirming technical feasibility in high-solar regions while optimizing battery numbers and PV efficiency for reliability and cost reduction. (Hamalai & et al, 2024) addressed the challenge of providing safe drinking water during military and emergency operations. They designed a mobile, dual-powered RO system to treat raw water on-site, overcoming issues of turbidity, hardness, microorganisms, and heavy metals. Using Autodesk Inventor and durable materials, the plant incorporated sediment and carbon filters, ion exchange, RO membranes, pre-polishing filters, and UV disinfection. Truck-mounted and solar/conventionally powered, it delivered 2.16 m³/day, sufficient for ~500 cadets. Tests on river, runoff, and pond water reduced turbidity from >1100 to 4.05 NTU, hardness from 208 to 60 mg/L, and eliminated coliforms and E. coli, while heavy metals were partially reduced. The study concluded that mobile RO units are reliable for military and emergency use and recommended scaling for heavy metal removal and civilian disaster relief. (El-Azizi & et al, 2003) addressed the challenges of establishing large-scale seawater reverse osmosis (SWRO) plants in arid regions with limited freshwater resources. The study focused on Tajura, Libya, where conventional water sources were insufficient for the growing population. Key challenges included feed water salinity variations, scaling and fouling potential, and high energy demands. The objective was to define design criteria for efficient, sustainable, and cost-effective operation of a 10,000 m³/day plant. Using engineering design principles, hydraulic modeling, and site-specific data, the study considered raw water characteristics, pretreatment, membrane selection, recovery ratios, pumping requirements, and energy recovery. Operational strategies included fouling prevention, optimal membrane arrangement, and energy optimization. Results demonstrated that appropriate intake design, membrane selection, and energy recovery significantly enhanced performance and reduced unit water costs. The study concluded that such a plant could reliably produce potable water meeting international standards while remaining economically viable and recommended that future large-scale desalination projects adopt integrated technical, economic, and environmental design criteria to ensure long-term sustainability. Groundwater salinity in Al-Butana region poses a critical challenge for potable water supply. This study presents the design and evaluation of a reverse osmosis (RO) unit to address saline intrusion and water scarcity. The proposed system demonstrates high salt rejection, reliable operation, and optimized energy consumption. Results confirm its effectiveness in producing safe drinking water from brackish groundwater. The design provides a practical solution for sustainable water management in the region

3 Material and Methods

The Al-Butana region in central Sudan suffers from severe potable water scarcity due to the high salinity of groundwater sources. To address this challenge, a reverse osmosis (RO) desalination plant with a design capacity of 705.8 m³/day was developed. Reverse osmosis was selected owing to its high salt rejection efficiency, operational reliability, and suitability for brackish groundwater conditions. The design process covered all treatment stages, from pretreatment to final disinfection, and was based on local hydrochemical characteristics.

Raw and treated water quality were evaluated to ensure compliance with WHO drinking water standards

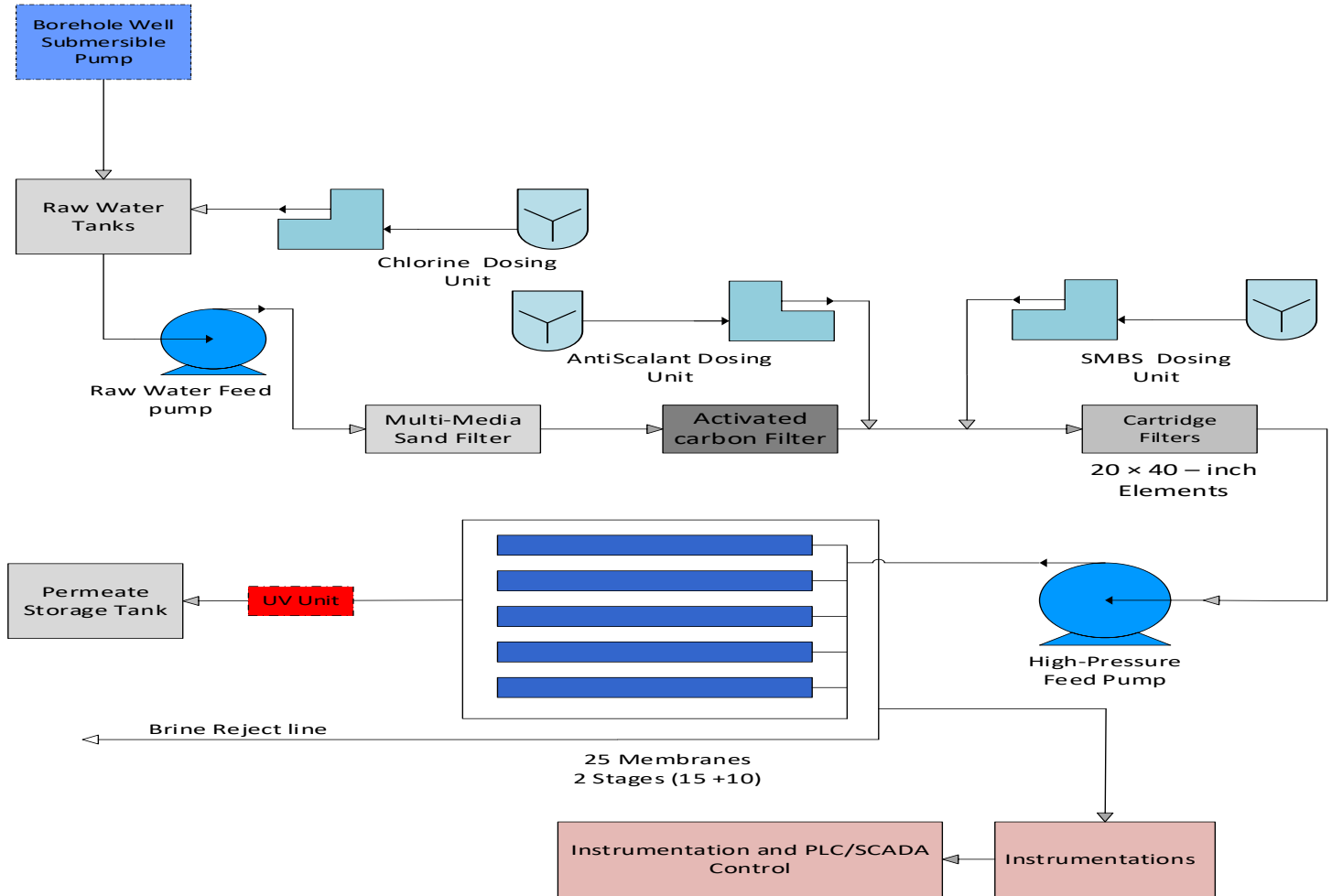
3.1 Materials Used for Fabrication

The reverse osmosis plant utilized corrosion-resistant piping and valves suitable for saline water. Transfer and high-pressure pumps were manufactured from duplex stainless steel or epoxy-coated cast iron to withstand corrosion and erosion under variable pressures. Pressure vessels housed spiral-wound thin-film composite polyamide membranes selected for high salt rejection and compatibility with brackish groundwater. Cartridge filter housings were made of stainless steel 316 or fiber-reinforced plastic to ensure durability and resistance to chemical cleaning. Thin-film composite polyamide membranes were used as reverse osmosis elements due to their high rejection efficiency and long service life. Chemical dosing systems were applied for antiscalant addition and controlled chlorination based on feed water chemistry. Raw and product water storage tanks were constructed from non-reactive materials to maintain water quality. Pretreatment consisted of multimedia filtration units and 5 µm cartridge filters to protect the membranes from fine particulates

3.2 Procedure and Method

The procedure commenced with raw groundwater extraction and initial sedimentation to remove suspended solids, followed by transfer to multimedia filters for further particulate and organic matter reduction. The pre-treated water was then passed through cartridge filters to protect the reverse osmosis membranes, prior to high-pressure pumping into the RO unit equipped with energy recovery devices. Antiscalant and chlorine dosing were applied as required to prevent scaling and biofouling. Post-RO permeate underwent ultraviolet disinfection before storage in the product tank, while concentrate was discharged. Water quality parameters were monitored throughout using standard analytical equipment to ensure compliance with SSMO and WHO guidelines. Water quality analysis was performed using standard laboratory instruments, including a DR3900 VIS spectrophotometer for physicochemical parameters, an HQ40d multimeter for pH, TDS, conductivity, and sodium, analytical balances, filtration manifolds, and incubators for microbiological analysis. These instruments ensured accurate monitoring of raw and treated water quality throughout the study.

Process Flow Diagram of the Designed RO Treatment System



3.3 System Design

Design calculations were performed for all treatment units based on a plant recovery rate of 85% and feed water TDS of 1000–1500 mg/L. The clarification (sedimentation) tank was designed as a pretreatment step to remove suspended solids and improve downstream performance. Key design parameters included detention time and surface overflow rate, which were selected according to standard engineering practice. Similar calculation procedures were applied to transfer pumps, multimedia filters, cartridge filters, high-pressure pumps, and the RO membrane system to ensure hydraulic balance, operational stability, and compliance with design objectives

3.4 Raw Water and Treated Water Analysis

The following table summarizes the average raw and treated water quality across all samples (A, B, and C) in comparison to the Sudanese Standards and Metrology Organization (SSMO) limits. Table 1: Summary of Raw and Treated Water Quality Parameters compared to SSMO Standards

Parameter	Unit	Raw Water Range	Treated Water Range	SSMO Standard
Turbidity	NTU	8.0–10.0	1.0	≤5.0
pH	-	6.2–6.8	7.1–7.5	6.5–8.5
Total Dissolved Solids (TDS)	mg/L	1400–1540	180–200	≤1000
Sodium (Na ⁺)	mg/L	90–105	16–19	≤250
Bicarbonate Alkalinity	mg/L	200–250	80–90	≤500
Magnesium (Mg ⁺²)	mg/L	100–120	10–12	≤50
Total Alkalinity	mg/L	270–300	110–140	≤500
Total Hardness	mg/L	300–360	80–90	≤500
Total Iron (Fe)	mg/L	0.14–0.18	0.009–0.014	≤0.3
Silica (SiO ₂)	mg/L	NIL	NIL	-
Sulphate (SO ₄ ⁻²)	mg/L	350–400	25–36	≤500
Calcium (Ca ²⁺)	mg/L	200–280	30–40	≤200
Arsenic (As)	mg/L	0.01	< 0.001	0.01
Cadmium (Cd)	mg/L	0.001	< 0.001	0.001
Lead (Pb)	mg/L	0.01	< 0.001	0.001
Mercury (Hg)	mg/L	0.001	< 0.0001	0.0001

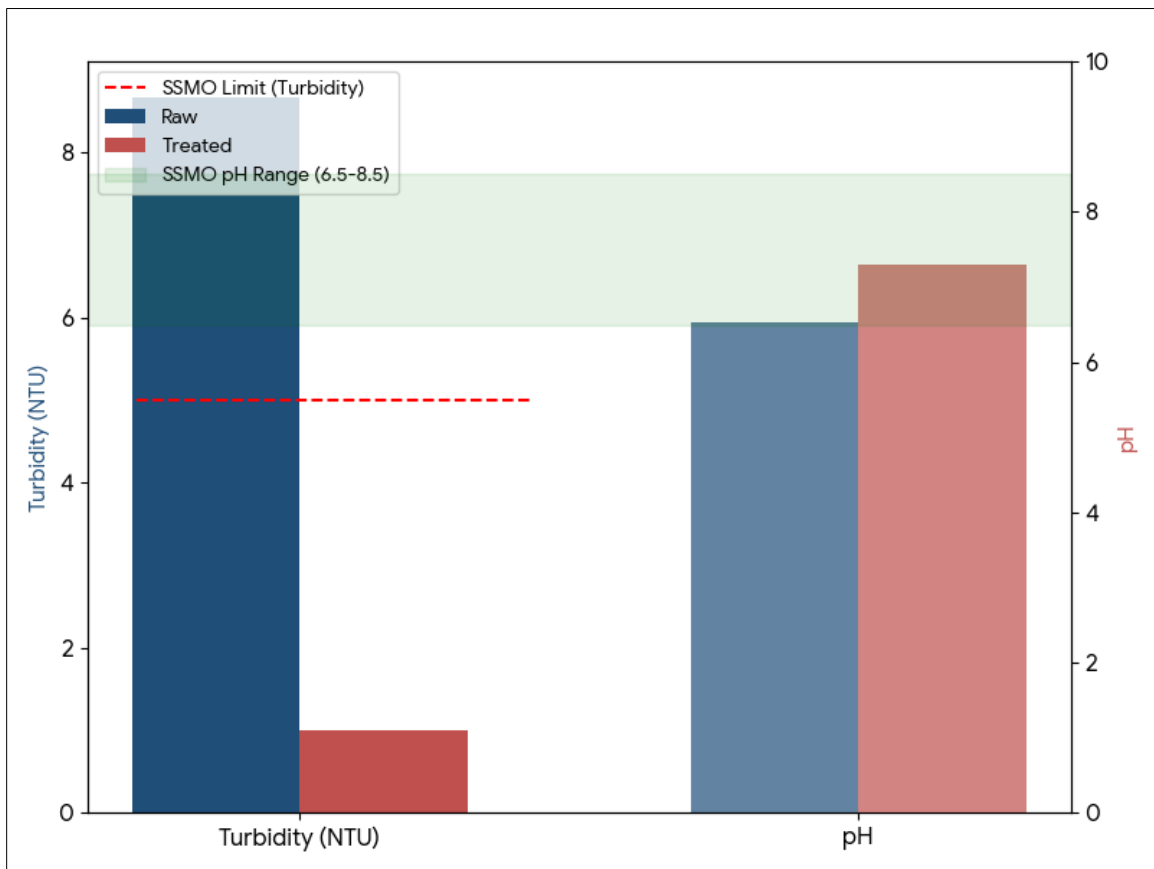
4 RESULTS AND DISCUSSION

The performance of the designed reverse osmosis (RO) unit was evaluated based on water quality improvement and system operational parameters. The results showed a significant reduction in total dissolved solids (TDS), turbidity, and major ionic constituents after treatment. The permeate water quality complied with international drinking water standards, indicating effective desalination and contaminant removal. The pretreatment system demonstrated stable operation, achieving low turbidity and acceptable silt density index (SDI) values, which are essential for protecting the RO membranes and ensuring long-term performance. The RO unit operated at the designed recovery ratio without signs of hydraulic imbalance or excessive pressure losses. Overall, the obtained results confirm that the proposed RO system design is capable of producing potable water efficiently from brackish groundwater, with reliable performance and suitability for application in water-scarce regions

4.1 Physical Quality and System Stability

The system's initial success is rooted in the physical preparation of the water. As illustrated in the Physical Quality Chart (figure 1), the pretreatment train—comprising sedimentation, multimedia, and carbon filters—was instrumental in reducing turbidity from a raw average of 8.67 NTU to a consistent 1.00 NTU. This significant decline ensures the final product is well below the SSMO limit of ≤ 5 NTU.

Furthermore, the RO process stabilized the water's chemical profile. The raw groundwater was slightly acidic (pH 6.2–6.8), which can be corrosive to metal infrastructure. The treated water was adjusted to a near-neutral range of 7.1–7.5, falling perfectly within the SSMO range of 6.5–8.5. This transition is vital for corrosion control and improving water



palatability.

Figure 1: Physical Quality: Turbidity and pH improvement

4.2 Mineral Removal and Desalination Efficiency

The Mineral Removal Chart (figure 2) highlights the high rejection efficiency of the RO membranes. The Total Dissolved Solids (TDS) dropped from a brackish average of 1,466.67

mg/L to approximately 193.33 mg/L. This represents a removal efficiency exceeding 85%, shifting the water from a "brackish" classification to a quality that meets international targets of 150–200 mg/L.

Key monovalent ions followed this trend:

- Sodium: Reduced from 90–105 mg/L to 16–19 mg/L, well below the 250 mg/L limit.
- Sulphate: Dropped from 350–400 mg/L to 25–36 mg/L, significantly reducing the risk of sulphate scaling and ensuring compliance with the 500 mg/L standard.

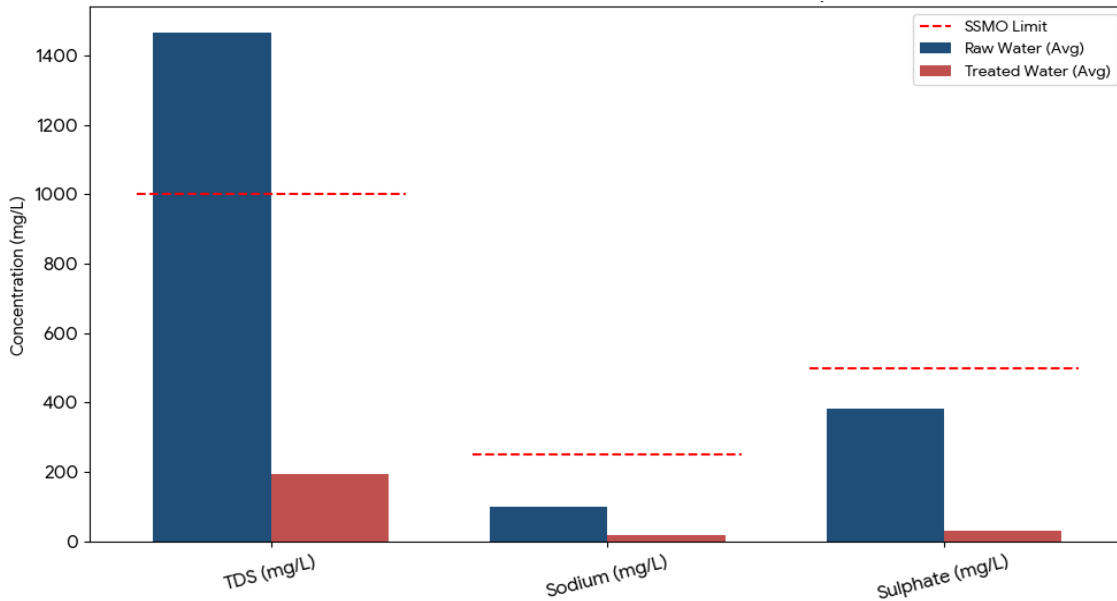


Figure 2: Mineral removal desalination efficiency

4.3 Hardness Reduction and Scaling Control

As shown in the Hardness and Scaling Control Chart (figure3), the RO system effectively "softened" the water by targeting divalent ions. Total Hardness was reduced from an average of 336.67 mg/L to 85.00 mg/L, converting the water from "hard" to "soft".

This reduction is a direct result of the membrane's ability to reject:

- Calcium: Concentrations dropped from 200–280 mg/L to 30–40 mg/L.
- Magnesium: Levels fell from 100–120 mg/L to 10–12 mg/L.
- Bicarbonates: Declined from 200–250 mg/L to 80–90 mg/L. These results are critical for preventing the buildup of scale in household appliances and industrial piping.

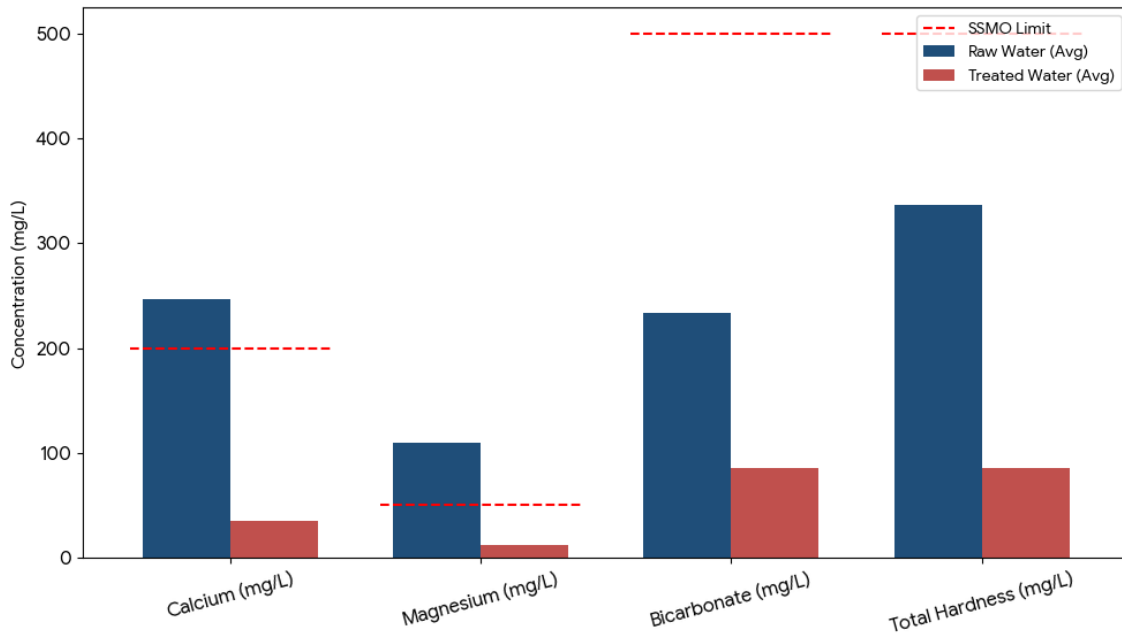


Figure 3: Hardness and Scaling Control

4.4 Toxic Metal Removal and Public Safety

The Toxic Metal Removal Chart (figure 4) underscores the most critical safety achievement of this study. The raw water contained Lead and Mercury at levels 10 times higher than the permissible SSMO limits.

The RO unit achieved over 90% removal efficiency for all heavy metals:

- Lead: Reduced from 0.01 mg/L to <0.001 mg/L.
- Mercury: Dropped from 0.001 mg/L to <0.0001 mg/L.
- Arsenic: Reduced from the threshold of 0.01 mg/L to <0.001 mg/L. By reducing these neurotoxic and nephrotoxic elements to nearly undetectable levels, the system guarantees that the water is safe for long-term human consumption.

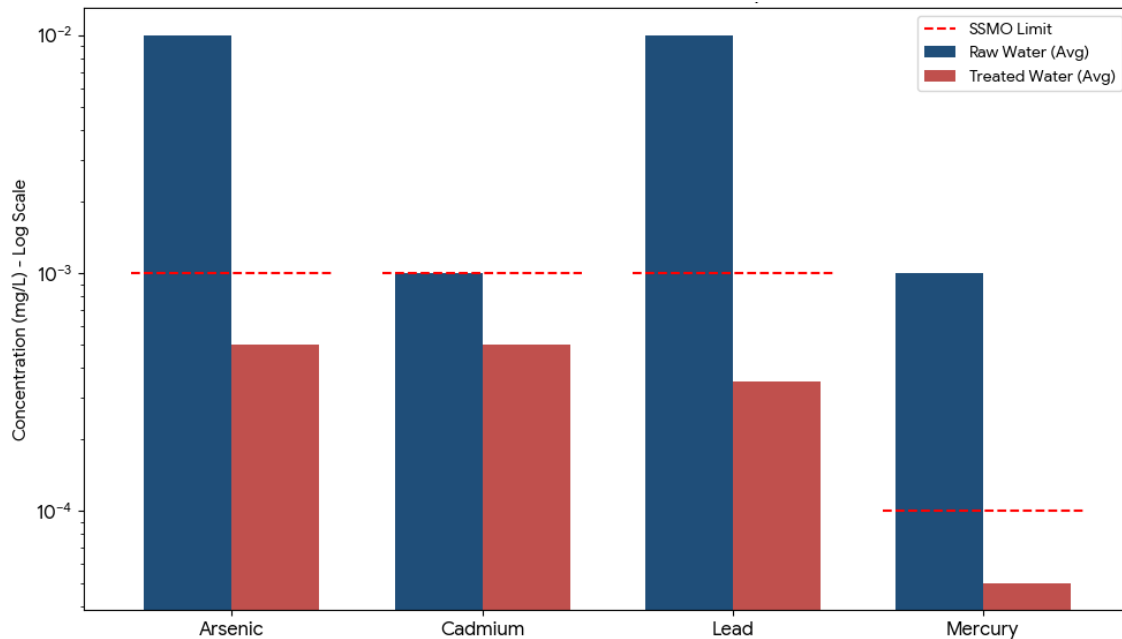


Figure 4: Toxic Metal Removal efficiency

4.5 Microbiological Safety

Finally, the microbiological analysis confirms that the RO system acts as a total barrier against pathogens. While the raw water showed bacterial contamination, the treated samples recorded NIL counts for general bacteria, coliforms, and *E. coli*. This proves the biological safety of the water and confirms that the RO unit effectively produces sterile, potable water that meets all health requirements.

4.6 CONCLUSION

This study demonstrates that the designed RO unit is a practical and highly effective solution for the AL-Butana region. By achieving high rejection rates for both dissolved minerals and toxic heavy metals, the system transforms non-potable, high-salinity groundwater into safe, high-quality drinking water that meets all SSMO standards.

5 References

- B. Penate & L. Garcia-Rodriguez, 2012. Desalination 284. s.l.:s.n.
- C. Fritzmann, J. Löwenberg, T. Wintgens & T. Melin, 2007. State-of-the-art of reverse osmosis desalination. s.l.:s.n.
- D.E. Sachit, & J.N. Veenstra, 2014. Journal of Membrane Science 453. s.l.:s.n.

David A. Ladner, et al., 2010) 490–499.. Evaluation of seawater desalination by reverse osmosis, *Desalination* 250, s.l.: s.n.

El-Azizi & et al, 2003. Design criteria of 10,000 m³/d SWRO desalination plant of Tajura, Libya, s.l.: s.n.

H. Hyung, & J.H. Kim, 2006. *Journal of Membrane Science* 286. s.l.:s.n.

Hamalai, S. & et al, 2024. Design and Construction of a Dual Powered Reverse Osmosis Based Mobile Water Treatment Plant for Military and Emergency Use, s.l.: s.n.

Kensara & et al, 2019. Reverse Osmosis Desalination Plant Driven by Solar Photovoltaic System, s.l.: s.n.

Mohammad A.K. Al-Sofi, et al., 2000. Optimization of hybridized seawater desalination process, *Desalination* 131 147–156, s.l.: s.n.

Muhammad Qasim, et al., 2019. A state-of-the-art review, *Desalination* 459. In: *Reverse osmosis desalination* . s.l.:s.n., pp. 59-104.

P.-K. Park, S. Lee, J.-S. Cho & J.-H. Kim, 2012. *Water Research* 46 (12). s.l.:s.n.

T.Y. Cath, A.E. Childress, & M. Elimelech, 2006. Forward osmosis: principles, applications, and recent developments *J. Memb. Sci.* 281. [Online]
Available at: <https://doi.org/10.1016/j.memsci.2006.05.048>.